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NO. 12574

IMPROVED FOUNDRY CASTINGS UTILIZING CAD/CAM

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U.S. ARMY TANK-AUTOMOTIVE COMMAND
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The CAD/CAM Casting process is being developed as an aid to casting engineers in designing better steel castings in a fraction of the time presently required. The computer routines incorporate drafting routines and computer assisted computations relative to heading and gating. Evaluation routines allow 2-D and 3-D heat flow analyses with a minimum of interaction from the user.

In Phase I, computer software has been developed for working with two

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dimensional sections of arbitrary casting geometries. A routine for automatic mesh generation has been developed to handle a limited range of geometries. A 3-D finite element method heat flow simulation has been developed and applied to computation of the freezing pattern in stepped plate sand mold castings. The results of the computer simulations were compared with the results of thermal measurement in eight armor steel plate castings molded and poured under commercial conditions.

Documentation for the currently developed software has been prepared as Exhibits 1, 2, and 3.

TACOM Report No. 12574 SETEC-MME-81-045

FINAL TECHNICAL REPORT

IMPROVED FOUNDRY CASTINGS UTILIZING CAD/CAM

DA PROJECT NO. 4775014

PHASE I

CONTRACT DAAK 30-78-C-0107

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OCTOBER 1981

MELTING AND SOLIDIFICATION LABORATORY
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FOREWORD

The work reported herein is the Phase I effort of an overall program to develop a computer aided process for designing the manufacturing process for high integrity steel castings. The program is sponsored by the U. S. Army Tank and Automotive Command (TACOM), Warren, Michigan under contract DAAK30-78-C-0107. Mr. Thomas Wassel has been the Project Monitor for Phase I. The work has been jointly conducted by the University of Pittsburgh, Battelle Columbus Laboratories, and Blaw-Knox Foundry.

Important contributions to this Phase I effort have been made by several individuals. Professors R. Smelser and T. W. Sze of the University of Pittsburgh offered guidance on design of the computer programs. J. Gasper, J. Farinelli, and J. Frizza of the University of Pittsburgh aided the thermal analysis (Section 3.0). G. Wilson of Battelle contributed to the design and development of the casting design programs (Exhibit I). T. Altan of Battelle, J. Duggan, E. Rowe, and J. Echlin of Blaw-Knox offered suggestions and helped to expedite project work.

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1. INTRODUCTION

This report discusses Phase I of the development of a system for designing molds capable of yielding a variety of uniform, high quality armor steel sand castings incorporating techniques of computer aided design and manufacturing (CAD/CAM). A system of programs, CAD/CAM Casting Process, is being developed by the University of Pittsburgh, Blaw Knox and the Battelle Columbus Laboratories under contract to the U. S. Army Tank and Automotive Command (TACOM). The CAD/CAM Casting Process will utilize 2-D and 3-D computer graphics for displaying the components for interactive design of the mold and will incorporate heat flow, fluid flow, and stress analyses to provide for casting soundness. Although the programs being developed for TACOM are intended for armor steel castings, the computer routines will be applicable for steel castings in general. The CAD/CAM Casting Process is designed for use by foundry engineers with no previous programming experience.

In Phase I, 2-D computer graphics with assembly capability have been developed for interactive design of the mold configuration and semi-automatic analysis routines for 2-D and 3-D heat flow and fluid flow have been developed. Brief descriptions of the routines are given in the following sections and more detailed documentation is given in Exhibits 1, 2, and 3.

Additionally, stepped plate castings have been cast under commercial conditions to gather heat flow and soundness data for input to the programs.

2. THE CAD/CAM CASTING PROCESS

The CAD/CAM Casting Process is aimed at providing a computer aided design tool for the casting engineer. It represents an integrated set of programs covering the two following areas:

a. A framework for utilizing computer graphics to handle and display cross-sectional geometry as well as calculate geometric parameters relative to heading and gating.

b. Evaluation of mold cavity design by finite element analysis of the solidification process. Facilities are provided for defining a simplified three-dimensional mathematical model of the casting. Actual mesh generation for the analysis is completely automatic. Output in the form of heat transfer plots and solidification maps will serve to predict casting soundness.

The overall design of the CAD/CAM Casting Process is illustrated in Figure 1. It is intended that the programs will be used by casting engineers who do not have detailed understanding of computer techniques or finite element analysis. The casting engineer will have the facility to make accurate analysis of the freezing

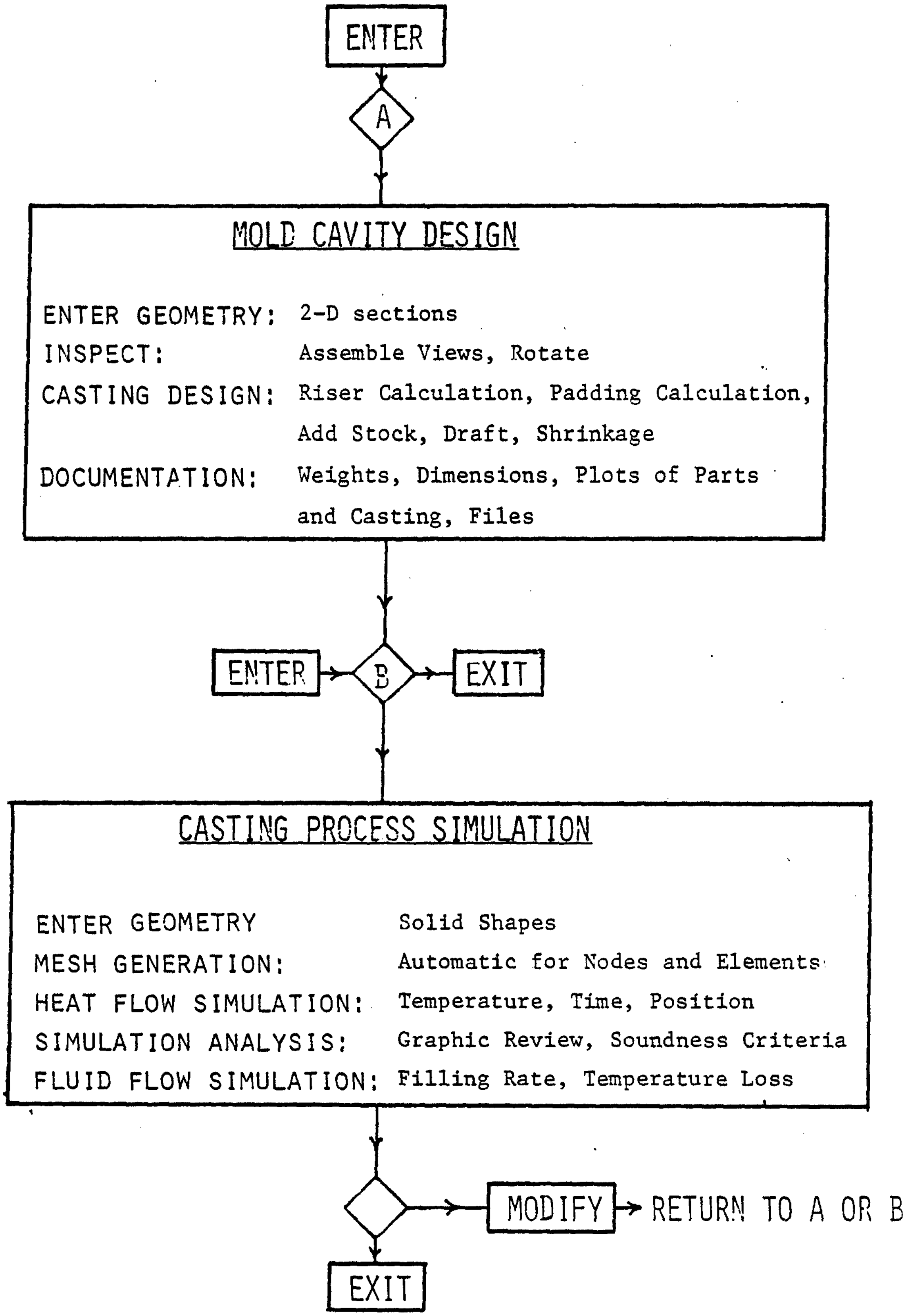

Figure 1: Overall design of CAD/CAM Casting Process

process reserving for himself the decisions relative to heading and gating and having the program automatically, inexpensively, and rapidly handle the details of the analysis. Facilities will also be available for casting engineers with a strong background in computer analysis to over-ride the computer routines in guiding the analysis.

2-1 Mold Cavity Design Routines: CADSEC

The mold cavity design routines are primarily a drafting tool that makes use of two input devices and a graphics screen. The input devices are a function keyboard and a digitizing tablet. With the keyboard, coordinates of points describing the perimeter of a cross-section can be input. Twenty-five points per cross-section can be used. With the use of different function keys, the points can be joined by straight lines, arcs or smooth curves. The cross-section is then viewed on the graphics screen.

Figure 2 is an example of cross-section data input via the function keyboard. With the digitizer tablet, cross-sections can be input by pressing points on the tablet with a light pen. Sections or views of a scaled blueprint can, in that way, be "traced" onto the screen. Several subfunction keys aid in this process. For instance, a circle can be traced by digitizing the center and one point of the circumference, an arc of a circle by digitizing three points, and a smooth curve by digitizing several points. The sections on the screen can be enlarged or reduced to any desired scale and shrinkage allowances added.

When all the cross-sections defining a casting have been fed to the computer, the computer can be ordered to display a three dimensional, isometric view of the casting. This 3-D view can be rotated and seen from different angles.

At this time, the casting engineer is ready to interact with the computer by adding machining allowances, back-ups, tapers, fillers, etc. again using the graphics terminal. The computer can be ordered to inscribe circles along a cross-section and to display the diameters of these circles. It can also calculate surface areas and perimeters.

Then the casting engineer locates the calculated feeder pads, risers, chills, gating, etc. with the aid of the graphics terminal. Hard copies of the design are then automatically printed.

There are a total of 16 main function keys. Descriptions of some of the functions follow:

a. Activate the cross-section digitizing subsystem. The user can enter new sections via the digitizer tablet.

```
1, EXAMPLE DATA SET IN FORMAT TYPE 1
0, 0.0, 0.0, 1.0, 0.0
-1.5, 0.2, 0.0, 0.0
-1.4, 1.8, 0.0, .250
-0.9, 1.4, 0.0, .250
-0.9, 0.6, 0.0, .500
 1.0, 0.6, 0.0, .375
 1.0, 1.2, 0.0, .375
 2.2, 1.2, 0.0, .375
 2.3, 0.2, 0.0, 0.0
 2.2, -1.0, 0.0, .375
-1.4, -1.0, 0.0, .375
-1.5, 0.2, 0.0, 0.0
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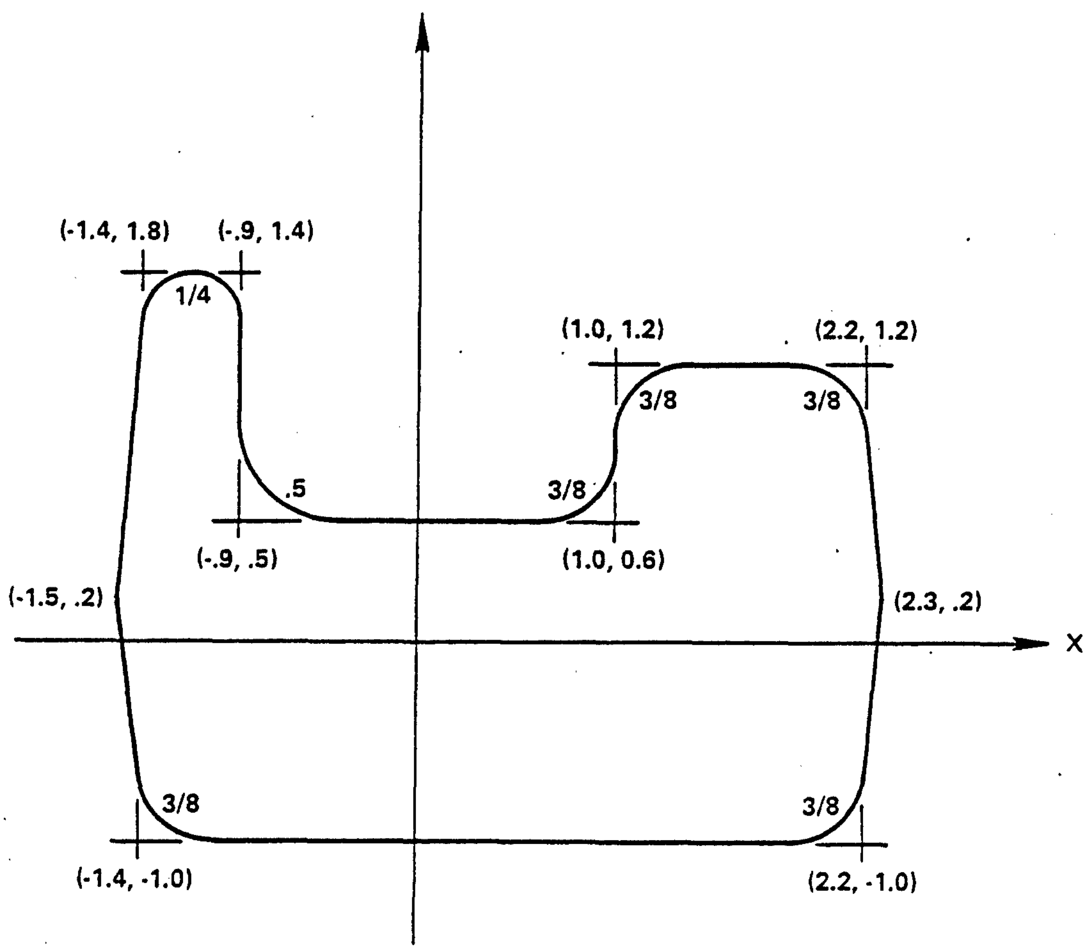


Figure 2: Example of Cross-Section Data Input

b. Activate the display management subsystem. Display orientation, display size, and number of displayed entities can be changed.

c. Edit Sections. This function provides the facilities for graphical editing of cross-sectional data. Subfunctions such as moving, scaling, rotating, copying, mirroring are available.

d. Activate the subsystem for performing casting process design calculations on cross-sections.

e. Activate library search subfunction. This will enable designers to search through existing designs for cross-sections similar to the one being worked on. In addition, frequently used shapes can be stored and recalled to minimize time and effort required to define a new geometry.

f. Copy the contents of the graphics screen to the X-Y plotter.

These routines, termed CADSEC, are incorporated in BCAST; and their capabilities and use are described in more detail in Exhibit 2.

2-2 Analysis Routines

To evaluate a mold cavity design, such as a design developed using CADSEC, routines are available to perform heat flow and fluid flow simulations. As a first step the geometry of the mold cavity and flask must be described, this time in terms of simple geometrical shapes called zones. The zones are then divided into nodes and elements creating data input files for the analysis routines. Two routines were developed for entering simplified geometric models and mesh generation. BCAST was developed for semi-automatic mesh generation. However, because it was not available at the time the heat flow simulation routines were under development, a less general and less automatic mesh generation routine, AGRID, was developed. The mesh generation routines of BCAST have not been interfaced, yet, with the heat flow simulation routines of CSSP (described later).

2-2a Mesh Generation

2-2a (1) BCAST

As mentioned above the geometry of the mold cavity, including risers and flask are described to the computer in terms of zones using interactive graphics. The shapes implemented in Phase I include plates (bricks), and cylinders.

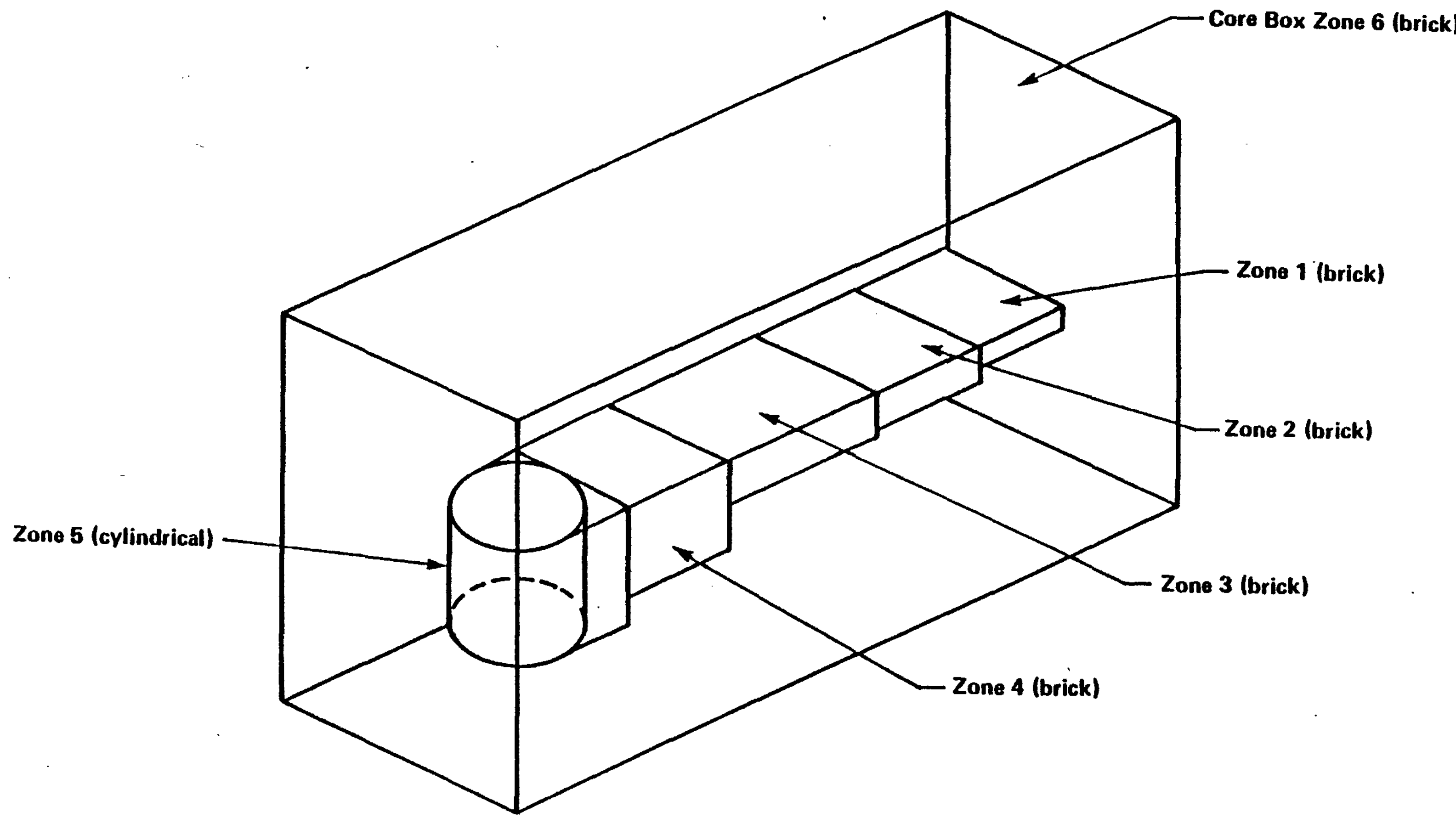


Figure 3: Drag Portion of Stepped Plate Casting Model Used for Mesh Generation

Other type of zones, e.g. truncated cones, hollow cylinders, and hollow cones, have been planned for Phase II. Figure 3 illustrates the division of the drag of the mold into five zones for a test plate casting used in the experimental portion of the project plus one additional zone to represent the sand in the core box.

A significant objective of the evaluation routines is that, opposed to other existing analysis routines, the nodal mesh for finite element analysis is generated automatically with little interaction by the user. The discretization of the geometric model is the first of a series of steps that must be performed when solving a problem using FEM. Unfortunately, this particular step does not have a theoretical basis. It is an art and depends on the use of engineering judgment. The application of poor or improper judgment will produce inaccurate results even though all of the other steps are rigorously adhered to. The elements chosen are small enough to keep the computational effort within practical limits. In a three dimensional analysis of a complex casting, several thousand nodes may be selected. The preparation of this input, if done manually (i.e., by punching cards), would be tedious and subject to human error. The logic used by the evaluation routines of the CAD/CAM Casting Process to generate a mesh is to select smaller elements close to the interfaces between sand and steel. It is at these interfaces where temperature gradients are the steepest.

Program BCAST also distinguishes the metal nodes from the sand nodes, identifies the types of the generated elements whether brick or wedge, numbers the nodes and elements, and generates the X, Y, Z coordinates of each node. All of these generated data are stored in a data file to be used later by the finite-element analysis programs of mold heat flow, fluid flow and stress analysis to provide for castings soundness.

The current Users Manual for Program BCAST is Exhibit 1. Users Manual for this and other routines are being continuously updated.

2-2a (2) <u>AGRID</u>

The geometry of the mold cavity and flask (or core box) for a mold design may be entered and a mesh generated in simplified form using AGRID. This routine prepares the data file in form suitable for direct input to the heat flow simulation routines, Casting Solidification Simulation Program (CSSP). All needed data are included. The output of AGRID is also used by the fluid flow simulation programs. AGRID only accepts five brick shaped zones. The mold is divided into elements by defining planes cutting the X, Y and Z directions. Only brick elements are treated by AGRID. (CSSP will convert all elements to tetrahedrons.) A representation of the centerline of a stepped plate casting similar to those used in the experimental phase of this work is shown in Figure 4.

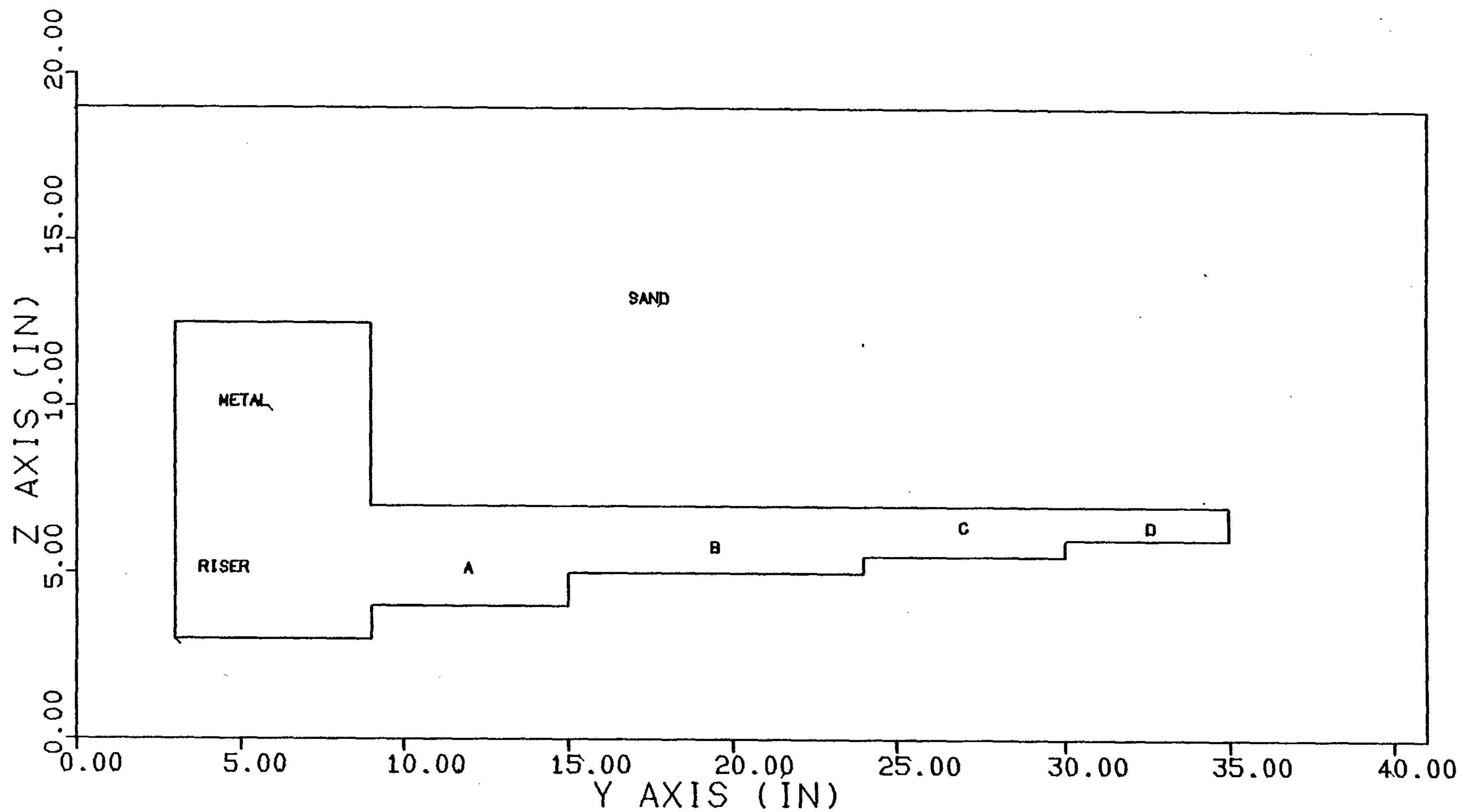


Figure 4: Centerline View of Casting Configuration

A description of the method of using AGRID is given in Exhibit 2. This mesh generation routine is used interactively on a teletypewriter terminal connected to a DEC 10 computer. The routines are written in FORTRAN and may be used with little or no change on other mainframe computer hardware.

2-2b Heat Flow Simulation: CSSP

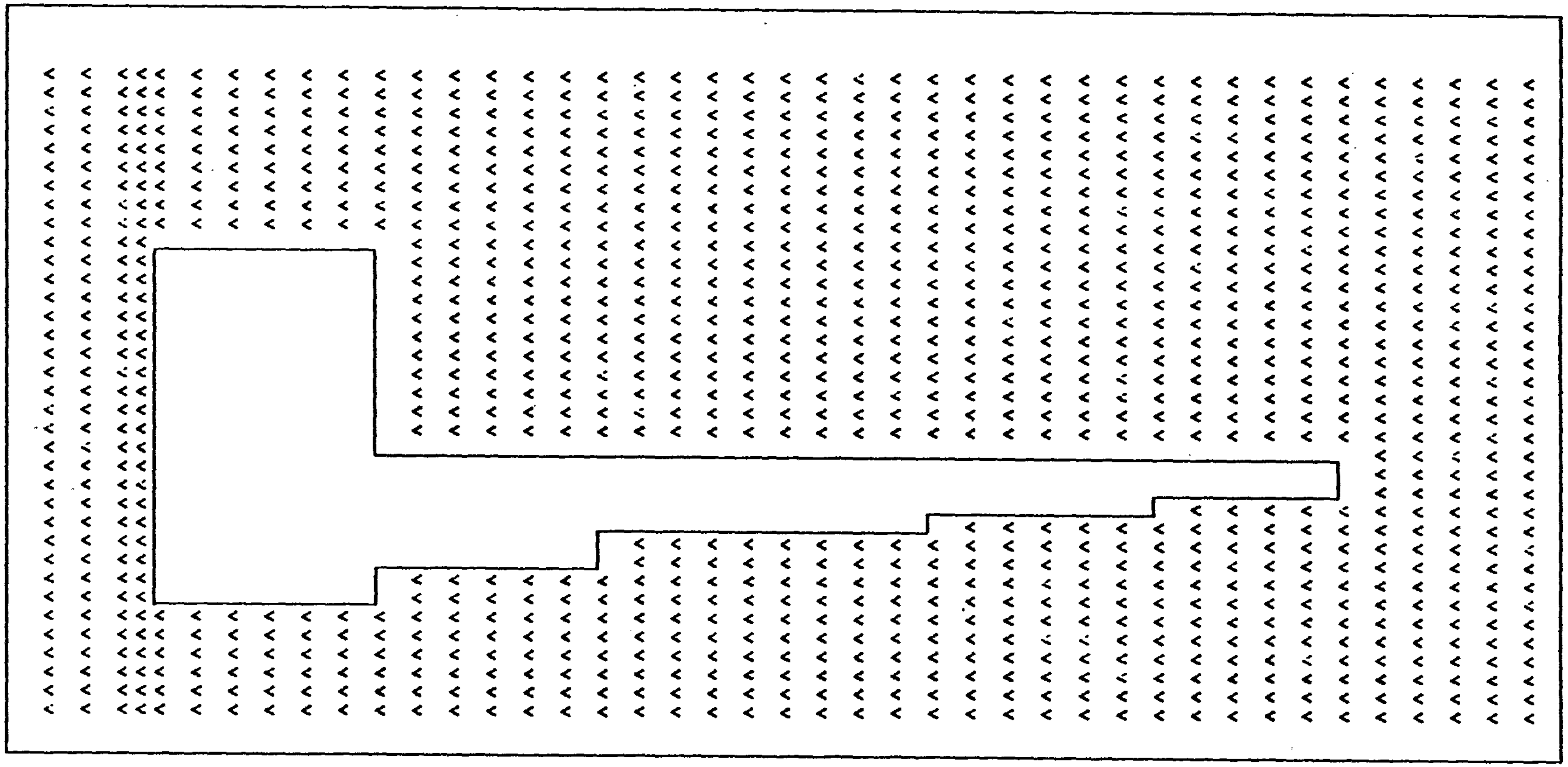
Another significant objective of the evaluation routines is to allow both two-dimensional and three-dimensional heat flow analysis. Two dimensional analysis of critical sections are economical in terms of computer time and analysis. Three-dimensional analysis will be useful for complex castings especially where lateral feeding is important.

The finite element heat transfer routines, CSSP, are designed to simulate arbitrary casting geometries considering conduction in the alloy and sand and convective loss to the ambient. It is assumed that risers and casting are filled instantaneously and then the cooling is simulated. Latent heat of the alloy is taken into account by modifying the heat capacity for the alloy within the mushy zone. The material thermal and physical properties are included in the data statements. These data are selected for armor steel/no bake sand. They may be easily changed for use with other alloy/mold material combinations.

Details of the basis and operation of CSSP are given in Exhibit 2. Again this routine has been implemented on the DEC 10 for interactive or batch processing. Because it is written in FORTRAN, it may be used with minor modification on other mainframe computer hardware. Results may be output on the teletypewriter, line printer, or put on tape for later post processing (as described in the next section).

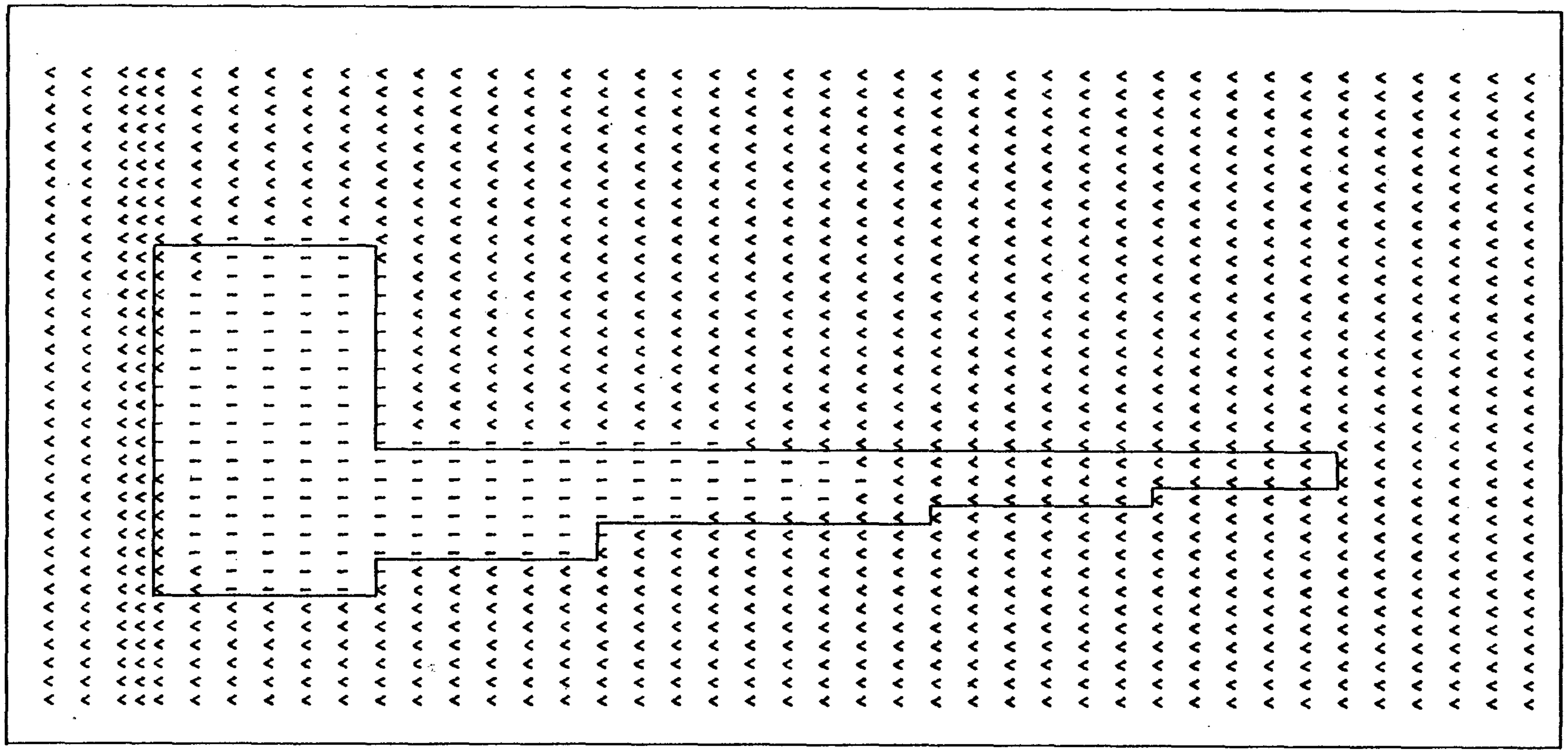
2-2c Presentation of Heat Flow Simulation Results

The results of the heat flow analysis may be viewed in several forms. One graphical representation is illustrated by Figure 5. The figure shows solid fication progression maps computed at different times after pouring a plate casting similar in design to those used in the experimental portion of the program. Arrow marks (" ") over nodes indicate solid steel and sand, dash marks ("-") indicate steel in the mushy state (partially solid), and blank nodes (" ") indicate liquid steel.



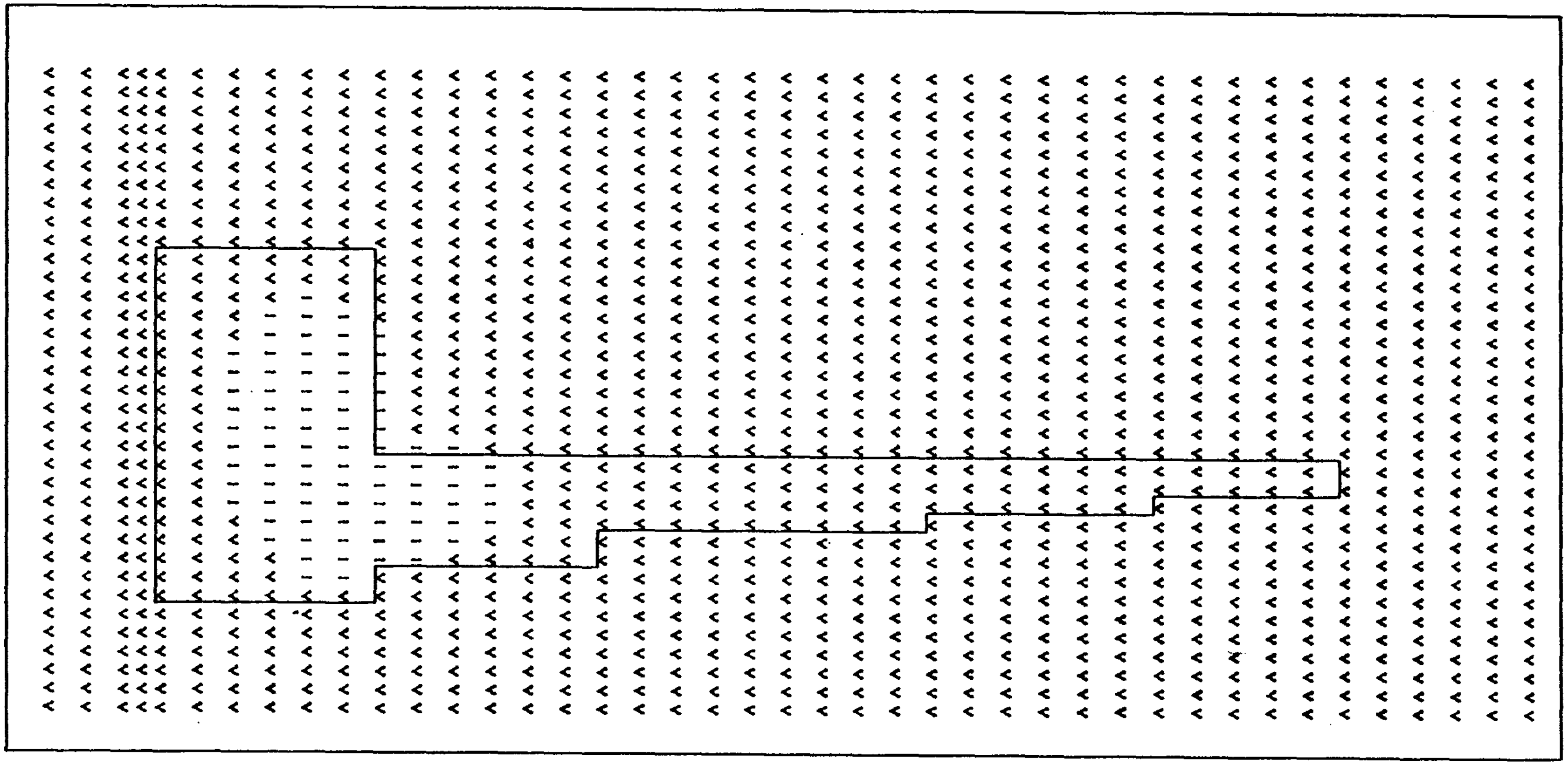
TIME (MIN) = 0.00

Figure 5a: Simulated Freezing Progression Map for Stepped Plate Castings, time = 0 minutes. (Sheet 1 of 3 sheets)



TIME (MIN) = 6.00

Figure 5b: Simulated Freezing Progression Map for Stepped Plate Casting, time = 6 minutes. (Sheet 2 of 3 sheets)



TIME (MIN) = 9.00

Figure 5c: Simulated Freezing Progression Map for Stepped Plate Castings, time = 9 minutes. (Sheet 3 of 3 sheets)

Other graphical representations include graphs of

(1). cooling curves, temperature versus time at different position

(2). temperature distribution, temperature versus position at different times

(3). cooling rates versus position at different times

(4). thermal gradient versus position at different times

Examples of these plots are included in Exhibit 2. Of course the results of the simulation may be printed in tabular form on the line printer.

2-2d Analysis of Gating System: FITLGS

Two calculations to simulate the gating system may be employed. One simulation computes the filling time of the casting. It also computes the flow rates and energy loss in the various parts of the gating system. A second simulation, using the result of the first, calculates the maximum temperature drop in the gating system. The latter computation is an aid in determining the pouring temperature. The procedure for using the gating system simulations are given in Exhibit 3.

3. STEPPED PLATE CASTING

Another objective of Phase I was to experimentally determine the thermal properties of the sand-alloy combination being simulated (cast armor steel-no bake sand) and to validate the computer simulations. Eight different stepped plate casting were cast at Blaw Knox. The pattern is sketched in Figures 6 and 7. The configurations of the plates are listed in Table 1. The chemical analysis for the eight test plate castings are given in Table 2.

The castings were instrumented for thermal analysis during freezing. Figure 7 shows the thermocouple locations. The Pt/Pt% Rh thermocouple tips were located at the mid-height of the plates at the locations shown. The thermocouple tips were protected by fused silica tubes. Millivolt readings for thermocouples 1-14 were recorded about every thirty seconds. The millivolt readings of thermocouples at the locations of highest cooling rate, 15 and 16, were recorded continuously. The resultant readings were entered into a computer for conversion to temperatures, plotting, and analysis. The castings were subsequently radiographed and heat treated. Mechanical testing of selected locations of the plates will be carried out in Phase II. These results will be utilized to develop appropriate soundness criteria. Machining of test specimens began in Phase I.

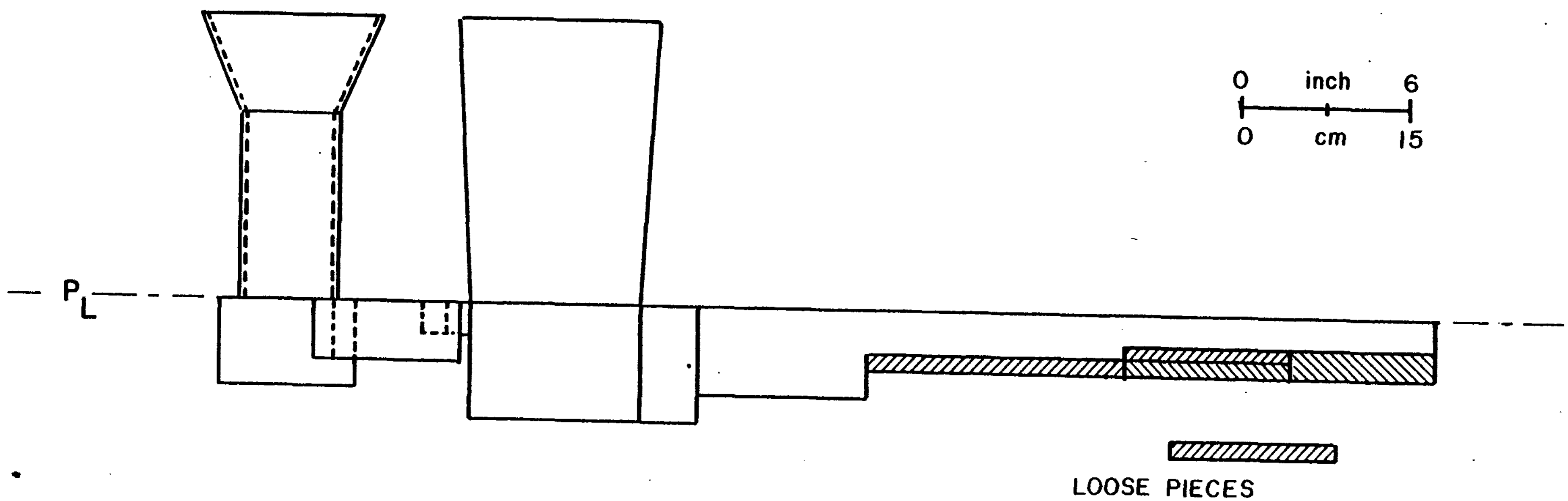


Figure 6: Side view of pattern for test plate casting

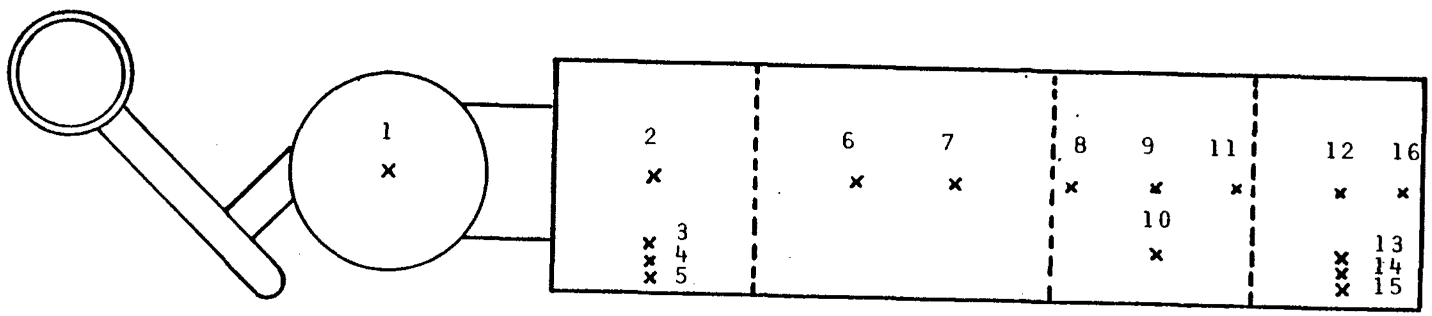


Figure 7: Top view of test plate castings indicating thermocouple positions

TABLE 1: Dimensions of test plate castings*

CASTING DESIGNATION	SECTION 1 6-in.lg.	SECTION 2 9-in.lg.	SECTION 3 6-in.lg.	SECTION 4 5-in.lg.	CHILL
A	3	2	1 1/2	1	no
B	3	2	1	1	no
C	3	2	2	1	no
D	3	2	2	2	no
E	3	1 1/2	1 1/2	1	no
F	3	1 1/2	1	1	no
G	3	2	2	2	yes
H	3	1 1/2	1	1	yes

*All castings were 7-in. wide

TABLE 2: Chemical analysis in weight percent of test plate castings

ELEMENT	Test Plate Casting Designation							
	A	B	C	D	E	F	G	H
C	0.25	0.27	0.30	0.25	0.26	0.28	0.30	0.28
Mn	1.00	1.20	1.26	1.18	1.28	1.25	1.08	1.20
Si	0.42	0.42	0.40	0.46	0.40	0.34	0.42	0.45
S	0.026	0.026	0.027	0.028	0.026	0.028	0.026	0.027
P	0.027	0.025	0.029	0.027	0.025	0.027	0.028	0.025
Cr	0.98	1.05	1.16	1.04	0.99	1.12	1.01	1.15
Ni	1.01	1,10	1.16	1.19	1.02	1.10	1.10	1.09
Mo	0.48	0.46	0.50	0.48	0.45	0.49	0.51	0.46

The stepped plate casting configurations mentioned in the previous section were simulated on the computer using the heat flow analysis programs. The computer and the experimental analysis were compared.

Figures 8 through 12 show some of the analysis of the thermal measurements for two castings, A and D. Casting A has four steps and by conventional design rules this casting should be sound. Casting D has only two steps. The twenty-inch long two-inch thick step would be expected, by conventional design rules, to show centerline shrinkage porosity. In line with our expectations, radiographic inspection of the two-inch sections showed casting A was sound and casting D had centerline shrinkage.

Figure 8 shows cooling curves along the centerline for casting A. The numbers on the curves refer to the thermocouple locations given in Figure 7. In the region above 2,600 F (the freezing range), the curves are well separated indicating directional freezing toward the riser. Figure 9 is another type of plot for casting A. In this case, temperature is plotted versus distance. The numbers on the curves indicate the time after pouring. The slopes of these curves are temperature gradients. Again, the curves of Figure 9 show the directionality of freezing for casting A.

Figure 10 shows the cooling curves for casting D. Again the numbers on the curves refer to the thermocouple positions in Figure 7. For this casting the cooling curves in the freezing range do not show directionality of freezing. Similarly, the temperature versus distance plots for casting D shown in Figure 11 indicate little directionality of freezing. Comparison of Figures 9 and 11 indicate, as expected, shallower thermal gradients in casting D.

Figure 12 depicts the thermal gradients (F/in.) measured within the freezing range along the lengths of the two castings. Casting A shows gradients over 3 F/in. at every point. Casting D, on the other hand, shows very low gradients in the center of the two-inch plate. The gradient increases near the riser and near the end of the plate (end effect).

The solidification progression maps in Figure 5 are computed for a casting with a stepped plate configuration the same as casting A, however, the riser in the computer simulated casting was smaller. The computed maps show a pattern of directional freezing. The computed analysis has also been used to show graphically the cooling curves, the temperature versus distance plots, and the thermal gradients in the freezing range plotted versus location along the centerline. (See Exhibit 2.)

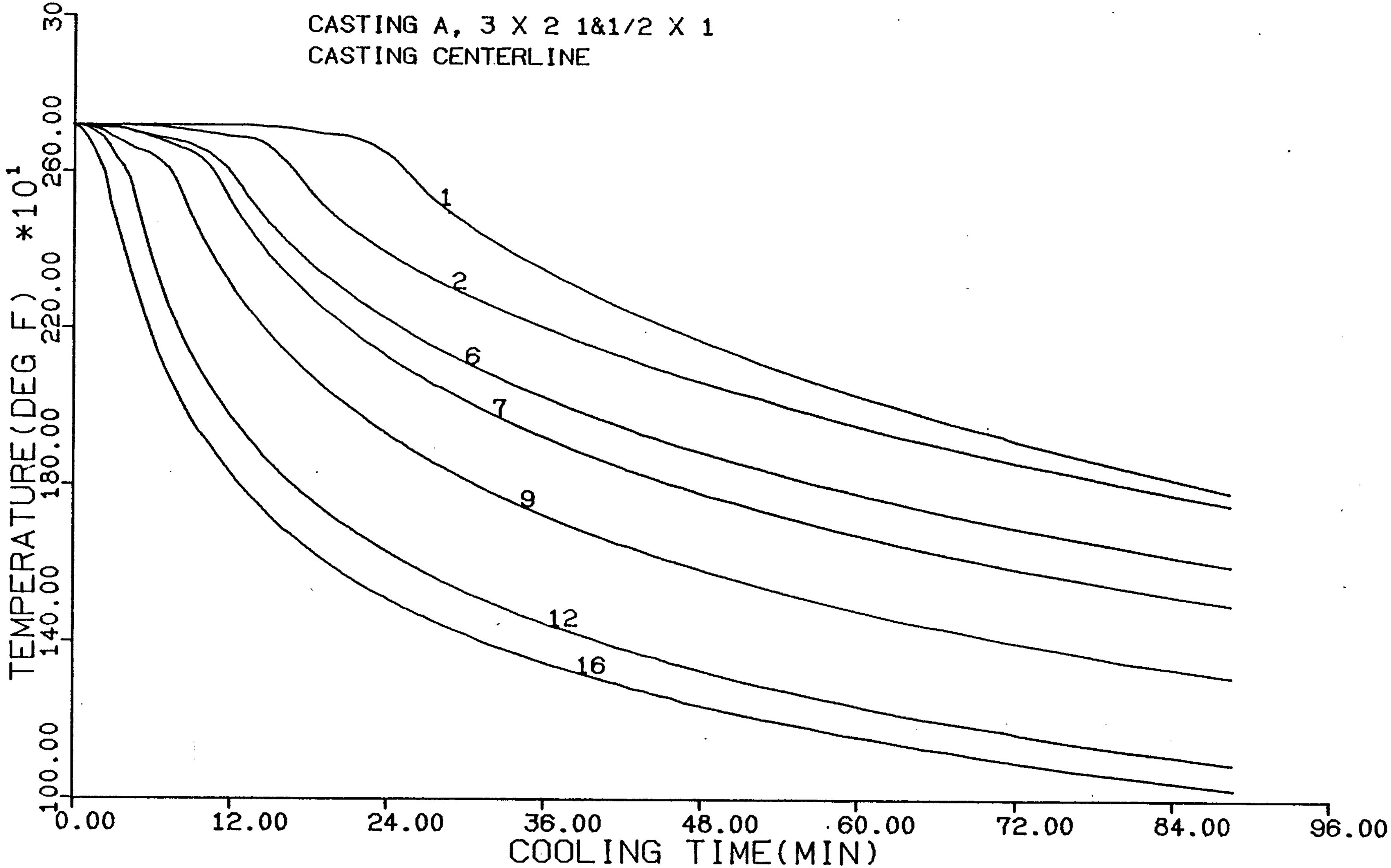


Figure 8: Cooling curves for casting A at centerline positions

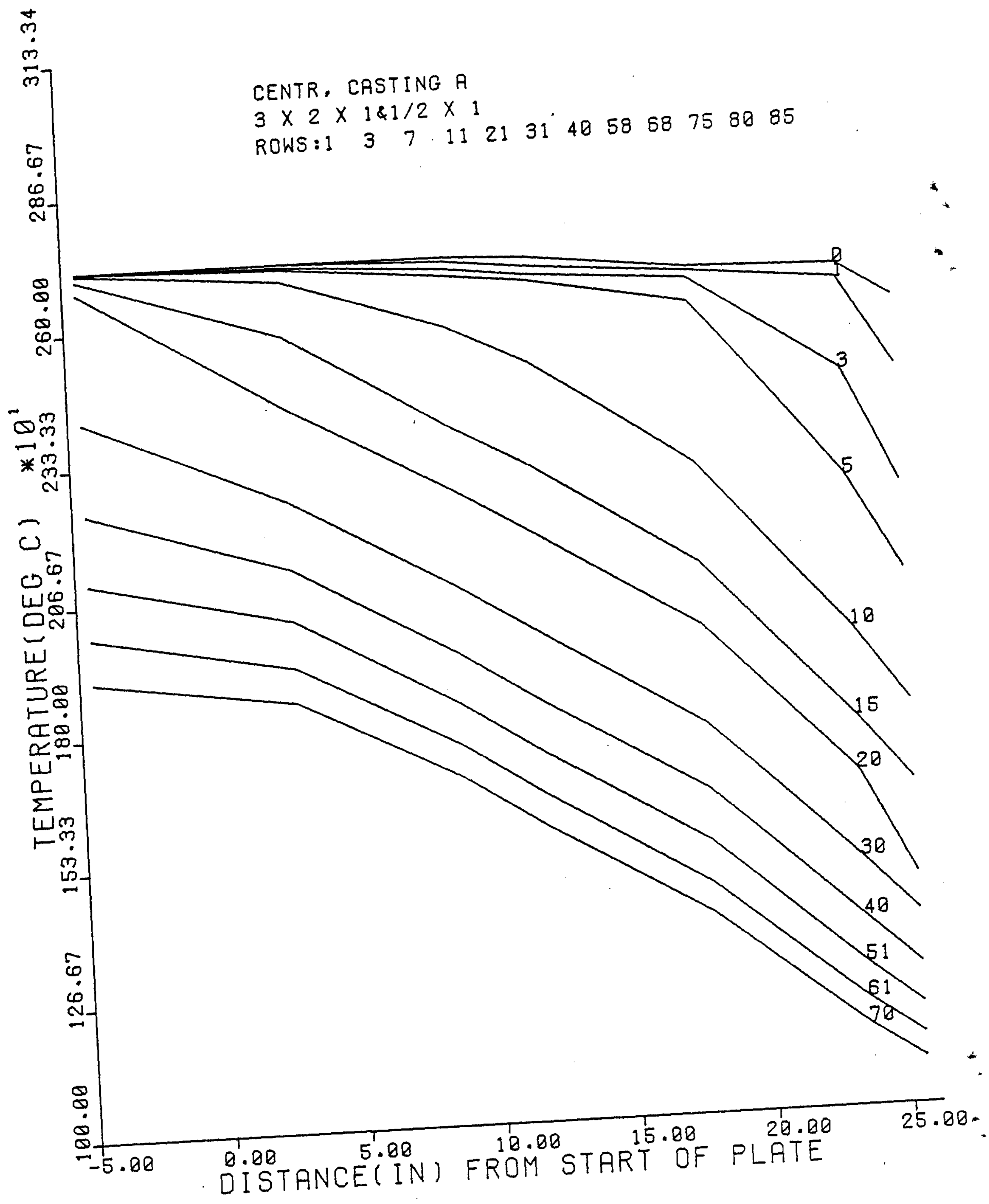


Figure 9: Temperature distribution along centerline in casting A at various times

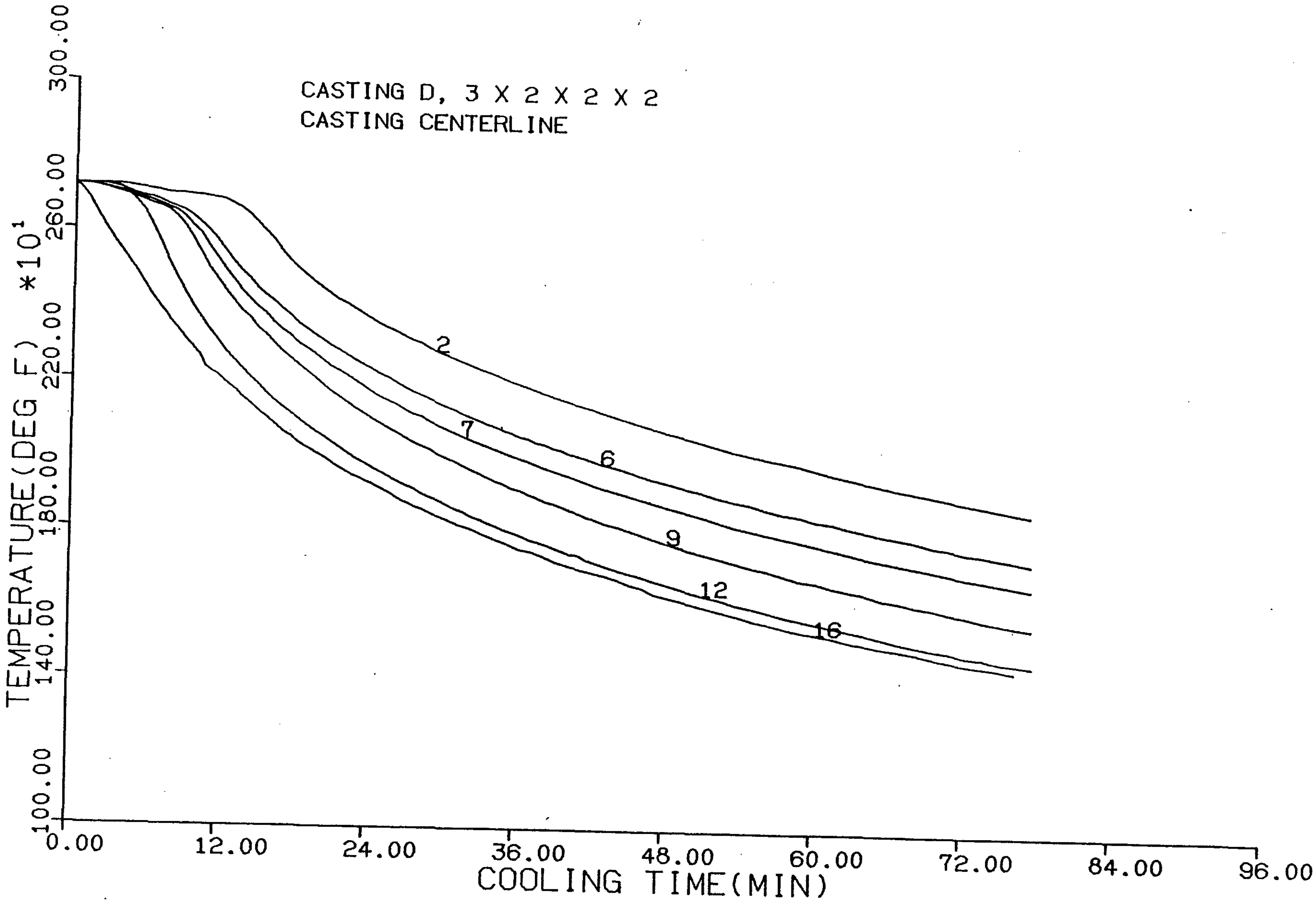


Figure 10: Cooling curves for casting D at centerline positions

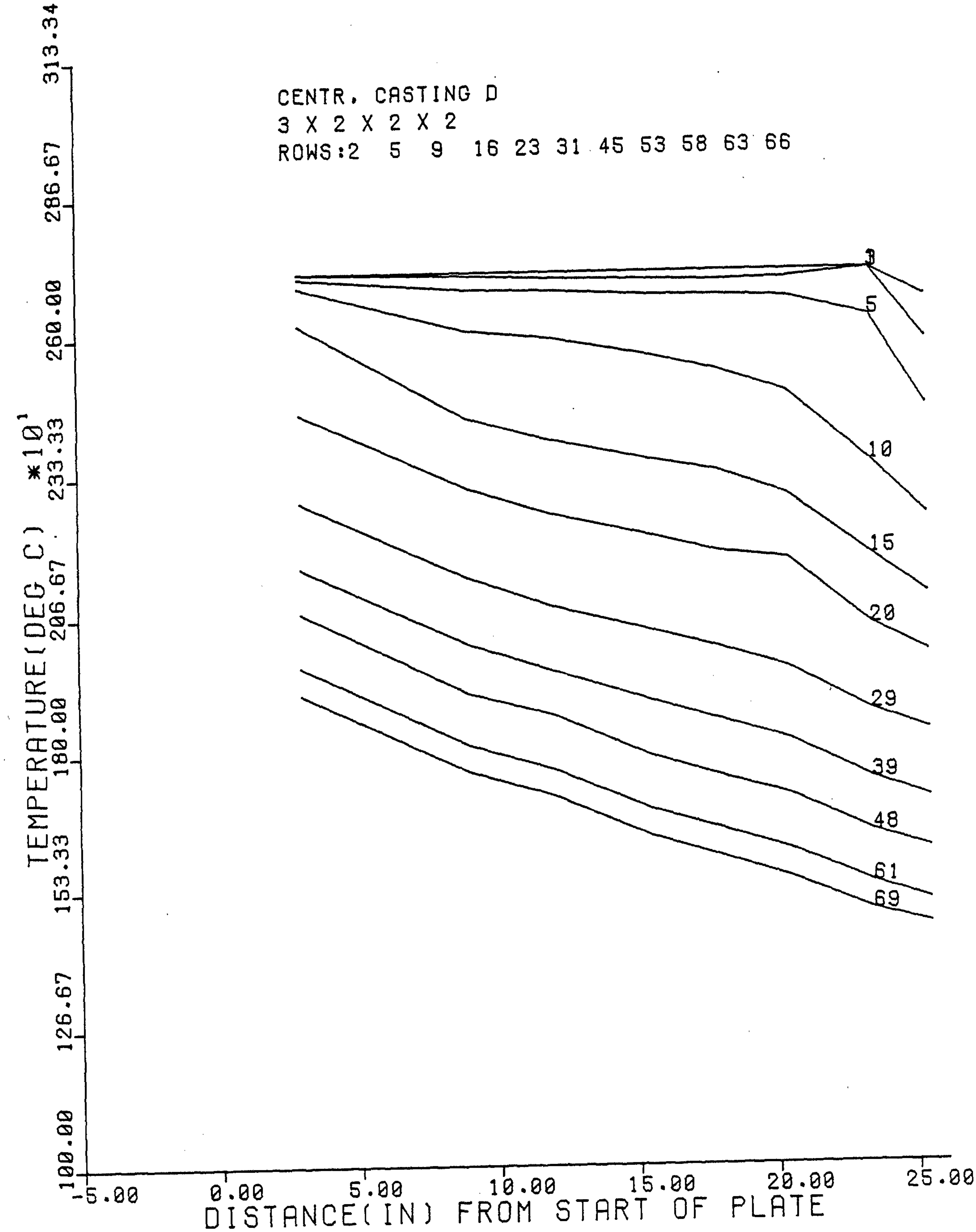


Figure 11: Temperature distribution along centerline in casting D at various times

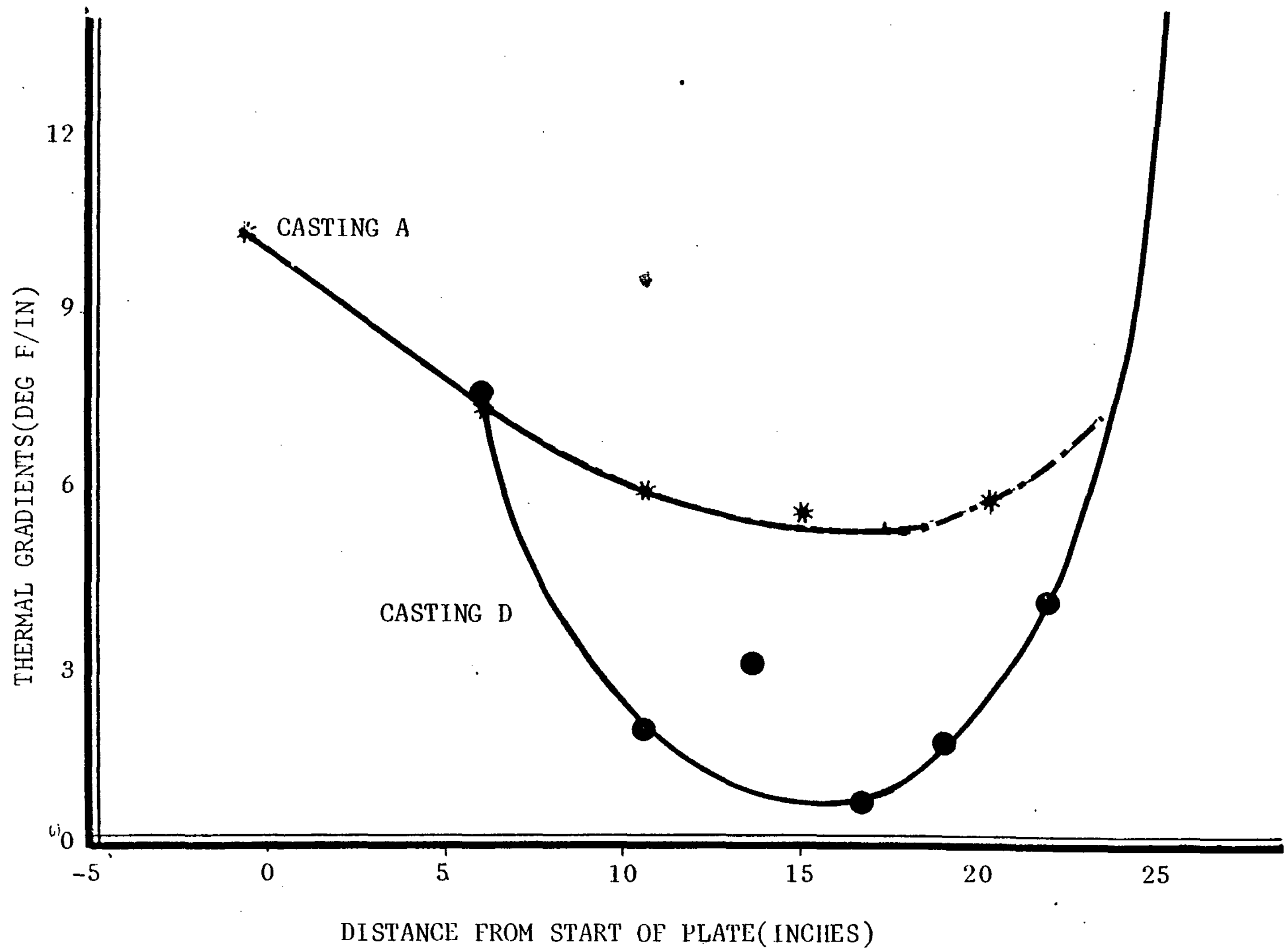


Figure 12: Thermal gradients along centerline in freezing range for castings A and D

4. SUMMARY

The CAD/CAM Casting Process represents an important step in the application of computers to casting engineering. Its ultimate goal is to provide working techniques for the design of better castings in a fraction of the time presently required.

In the CAD/CAM Casting Process, a system of programs incorporates regular computer aided drafting techniques plus a number of routines relative to heading and gating. Automatic mesh generation tied together with 2-D and 3-D finite element analysis allows for expedient heat flow simulations of castings in sand molds. Simple fluid flow routines allow for analysis of gating systems. It makes possible predictive evaluation of casting soundness.

Experimental heat flow simulations of eight test castings were used to determine heat transfer parameters for the alloy-sand combination. Computer simulations for the same test castings were found substantially in agreement with the experimental results.

5. RECOMMENDATIONS - PHASE II EFFORT

In the subsequent development of the CAD/CAM Casting Process, the experimental thermal data obtained from the test plate castings will be incorporated into the programs.

Mechanical properties and radiographic soundness of the test plate castings will be correlated with the computed and experimentally determined thermal conditions during freezing of the plate castings. These correlations will be used to generate criteria amenable to computer application for predicting casting soundness.

The routines for casting design and analysis developed individually will be tested together, proper interfaces developed and improvements in program design implemented. The capabilities of the routines will be expanded to handle more complex geometries and to offer more options.

A number of armor castings of increasing complexity will be simulated, cast and experimentally analyzed.

The techniques of the CAD/CAM Casting Process will be tested on these various castings in order to develop the potential of the programs.

Several alternative, parallel approaches to computer assisted design and simulation of the casting process have been explored and initiated in Phase I. These alternate approaches will be more fully evaluated and

developed if considered worthwhile. The approaches under strong consideration for inclusion within the options of the CAD/CAM Casting Process include:

a. Finite difference heat flow simulation. A general 2-D and 3-D finite difference solidification simulation has been developed. A semi-automatic grid encoding routine (similar in design to AGRID) has been developed. These routines are being compared to AGRID and CSSP finite element approaches as far as storage requirement, operating speed, stability, and generality.

b. Fluid flow analysis. 2-D open channel, transient fluid flow simulations have been developed to model the flow of a molten alloy into a mold cavity. The most successful approach to date has been the marker and cell (MAC) technique.

c. Detailed design and simulation. Experience has been gained with use of CDC2000, a computer aided drafting program which is available on a time sharing service (CDC cybernet), and with UNISTRUC, a mesh generating routine (also available on cybernet). These routines can be readily interfaced with the CAD/CAM Casting Process to allow capabilities in drafting and in mesh generation for users who want more detailed and accurate simulation results than would be obtained by the presently designed automatic and semi-automatic approaches.

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SETEC-MME-81-045

EXHIBIT 1

USER'S MANUAL

for

BCAST

COMPUTER-AIDED

DESIGN FOR CASTINGS

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E1-1 INTRODUCTION

BCAST is aimed at providing a computer-aided design (CAD) tool to the casting engineer. Specifically, it presents an integrated set of programs to achieve two objectives:

a. Automatic mesh generation for finite-element analysis of the casting process. For this purpose, BCAST provides facilities for defining a simplified three-dimensional mathematical model of the casting. Actual mesh generation is completely automatic.

b. CAD aids for performing conventional casting process design calculations on cross sections of the casting.

E1-1-1 Hardware and Software Configuration

The Phase I version of BCAST system of computer programs requires, minimumly, the following hardware and software configuration:

a. Software

(1). RT-11 Operating system version 3B or 4.
(2). Fortran compiler.
(3). DEC-Graphics-11 software package.

b. Hardware

(1). PDP-11 series minicomputer with at least 32 Kw memory.
(2). At least one hard disk drive; for example, an RK05.
(3). VT-100 compatible alpha-numeric terminal.
(4). VT-11 display processor, CRT and light pen.
(5). Function buttons, equivalent to LK-11 KB.
(6). Digitizer tablet with cursor.

The last two items (5 and 6) are required by only CADSEC, the computer-aided design with sections module. The graphics display hardware and software can be changed for other types of refresh graphic terminals with light pen support, with relative ease. CADSEC also supports an X-Y plotter. Either Tektronix plotters using an RS-232 interface or other plotters using an XY-11 type interface may be used.

All programs other than the device drivers for the X-Y plotter, digitizer tablet and the function button box are written in FORTRAN. They should be compiled to take advantage of the computational devices, such as floating point processors, on the target PDP-11 system.

E1-1-1a Software Overview

The BCAST software appears to the user to be one large program with several parts (modules), each of which provides a different service. This illusion is maintained to simplify the user's interaction with the BCAST software and to minimize the user's prerequisite knowledge of the computer's operating system. Internally the BCAST software consists of seven main programs "glued" together by a chaining operation which permits one main program to transfer control to another, by unified data file naming and handling conventions, and by similar user interfaces. Figure E1-1 is a block diagram depicting the major functions of the BCAST software, their relationship to each other, and their interaction with data files. The reader is asked to refer to this figure to follow the discussion below.

E1-1-1b File Types

(1). Zone Files: A zone data file contains the coordinate information necessary to define the spatial geometry of a casting. This file is created and modified by the DEFINE ZONES module. Zone files provide input to the GENERATE MESH module.

(2). Mesh Files: A mesh file contains the X-Y-Z coordinates and material type that define each node and the node numbers that define each element for a casting. A copy of the zone file used to create the nodes and elements is also contained in a mesh file. The mesh file is created by the GENERATE MESH module and may be examined by the VIEW MESH module. A future enhancement (the dotted REFORMAT MESH module), to the BCAST software will include the facility to convert the information in the mesh file to a format usable by a particular finite element analysis program.

(3). Section Files: These files contain the information needed to define the cross sections of castings. They are created by and used as input to the CADSEC module.

(4). ASC11 Files: These files contain cross-section information. They are coded in ASC11, created by the system editor and may be used as input to the CADSEC module.

E1-1-2 Major System Modules

a. BCAST Supervisor: The BCAST supervisor is the entry point to the BCAST software. The supervisor permits the user to enter any of the other BCAST modules; similarly, when any of the other modules are exited, control is transferred back to the supervisor.

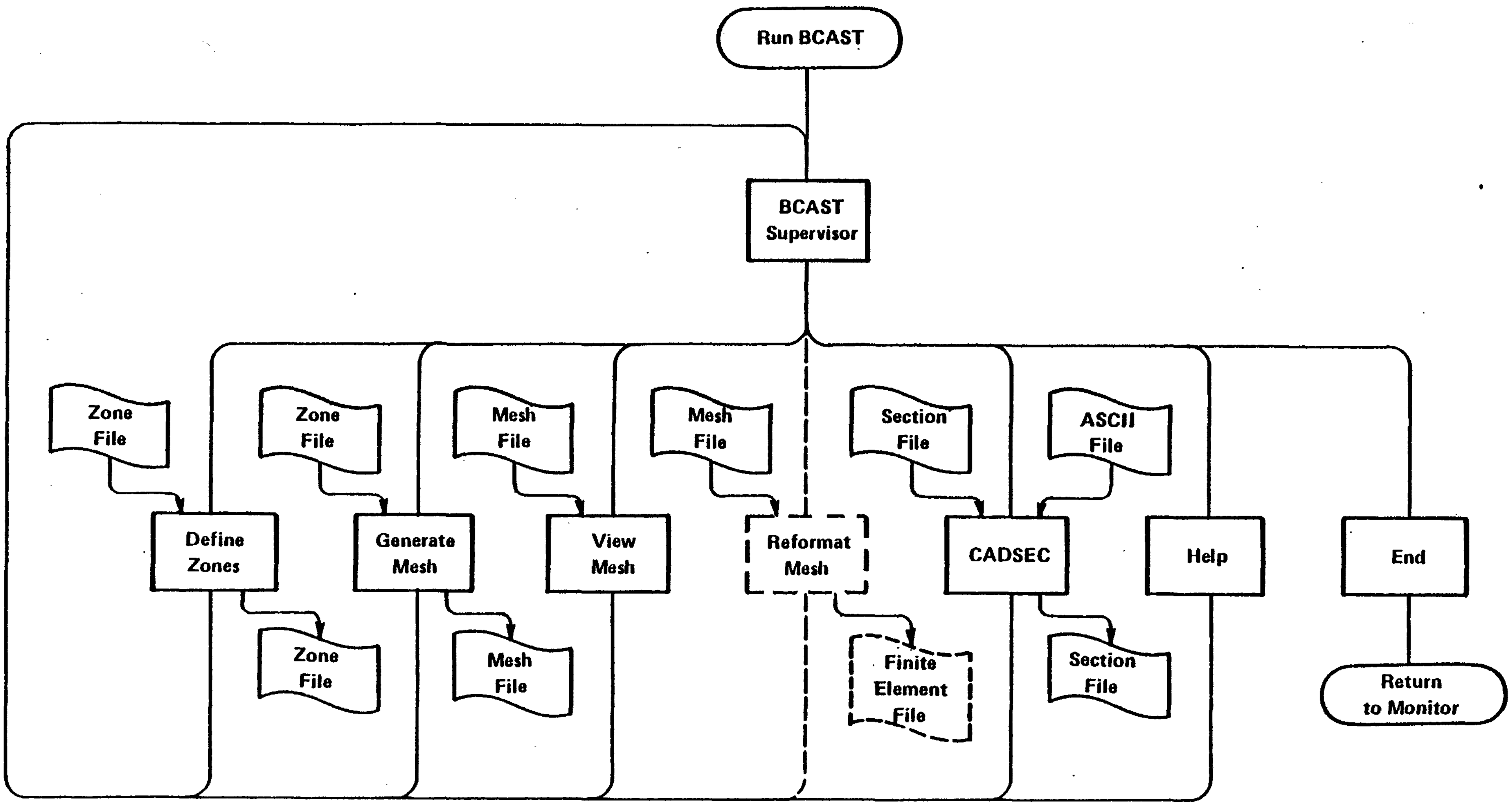

Figure E1-1: BCAST software block diagram.

b. Define Zones: This module enables the user to interact with zone files. The DEFINE ZONES module will work with an existing zone file or it may be used to create a new one. Individual zones may be added, deleted, or have their dimensions changed. The user may list the zones on the console or printer, display them graphically on the display screen, or have them drawn on the X-Y plotter.

c. Generate Mesh: This module produces a 3-dimensional finite element mesh from the geometry contained in a zone file. The mesh generation is automatic, requiring no interaction with the user. The node and element information generated by this module is stored in a mesh file.

d. View Mesh: The user can examine the contents of a mesh file with the VIEW MESH module. The display screen may be used to display any single layer of elements and the screen may be copied to an X-Y plotter. The coordinates and material type that define each node and the node numbers that define each element may be listed on the console or printer.

e. Reformat Mesh: This module, not implemented at the present time, would translate the internal format of mesh file to the format necessary for input to a specific finite-element analysis program.

f. CADSEC: Perform computer-aided design and casting-related calculations on cross sections.

g. HELP and END: The HELP module lists, on the console, a summary of the BCAST commands. The END module terminates the BCAST software package and returns control to the computer's operating system.

E1-1-3 General User Information

The user interacts with the BCAST software through the console, the graphics display, and the digitizer. User information for the graphics display and the digitizer is contained in the "Computer-Aided Design with Sections" section of this exhibit. The user supplies information to the BCAST software and directs its execution by responding to various prompting messages which appear on the console screen. The user enters his reply to these prompts by typing on the console's keyboard. The BCAST software will request three types of information from the user; these, as well as some general comments are described below.

a. General Comments: All responses are terminated by typing the RETURN key. The return key causes the software to check the reply for validity and take the appropriate action. The delete key (labeled DEL on the keyboard) erases the last character typed on the console. The DEL key permits the operator to correct typographical errors prior to terminating an entry with the RETURN key.

Some prompting messages contain a suggested or default value in brackets, [ ]. The bracketed value represents the most recently or most frequently used responses to the prompting message. The user may signify his acceptance of the default by simply pressing the RETURN key; or optionally, he may explicitly enter the bracketed value or a different value.

The BCAST software supports an 80-character type ahead feature which enables the user to anticipate the next question and answer it before the prompt is output. This is an efficient means for the experienced user to interact with the BCAST software. It should be avoided, however, by the novice user because (1) the resulting prompts and responses will appear on the console out of order and (2) it presumes that the prompts will be anticipated properly.

b. Command Input: Commands are entered to direct the execution of the BCAST software or to indicate which of several options are to be used. The BCAST software will prompt the user with a brief message indicating the type of command being requested. The commands and options are usually English-language words which may be entered completely or as abbreviations. These words may be abbreviated to the minimum number of characters that are needed to make the command or option unique. When an unrecognizable command or option is entered, all valid responses are listed on the console and the user is reprompted. The user may enter HELP when prompted for a command, to obtain a brief description of the commands available to him.

c. Numeric Input: A second type of information required by the software is numeric information. When the BCAST software prompts the user for a numeric value, it should be entered via the console keyboard. In the case of floating point numbers, decimal points are optional. An error message will be listed on the console and the user will be reprompted, if the numeric value is not within valid limits.

d. File Name Input: Complete file names are given by dev: flname.ext; where, dev is a valid RT-11 device, flname consists of from one to six upper-case or numeric characters and ext is from zero to three upper-case or numeric characters. For the BCAST software, the device and extension do not change and need not be entered. Therefore, when the user is prompted for a file name, only the flname field should be entered. Standard names have been adopted for the ext field; these are listed in Table E1-1.

TABLE E1-1. Standard File Name Extensions

Ext	File Type
.ZON	Zone
MSH	Mesh
SEC	Sections
RFM	Reformatted Mesh
ASC	ASCII Section Data

When a file name is entered, the software checks for the existence of a file with the entered name. Since two files cannot have the same name, if a conflict is found, the user is informed.

E1-2 GEOMETRY DESCRIPTION FOR MESH GENERATION

E1-1-1 Types of Geometric Elements

In order to define the geometry of castings in a manner suitable for entry into the computer, the model should be split to different building blocks or zones. The different types of these building blocks are shown in Figure 2.

As shown in Figure E1-2, a brick zone is defined using the X, Y, Z coordinates of the corner point (closest to the origin 0.0, 0.0, 0.0) X , Y , Z , the dimensions on the X direction X , the Y direction Y , and the Z direction Z . A cylindrical zone is defined using the X, Y, Z coordinates of the lower center X , Y , Z , radius R and height H and so on for the other zone types.

E1-2-2 Types of Zones Used in BCAST

Program BCAST uses two types of building blocks, called "Zones", to describe the geometry of castings. These are "Brick zones" and "Cylindrical zones". The other types of zones (e.g., cones, hollow cylinders, hollow cones.....etc.) are being planned for Phase 2 of this project. Figures E1-3 and E1-4 show an example of how the geometry should be described by dividing or splitting a casting into "zones".

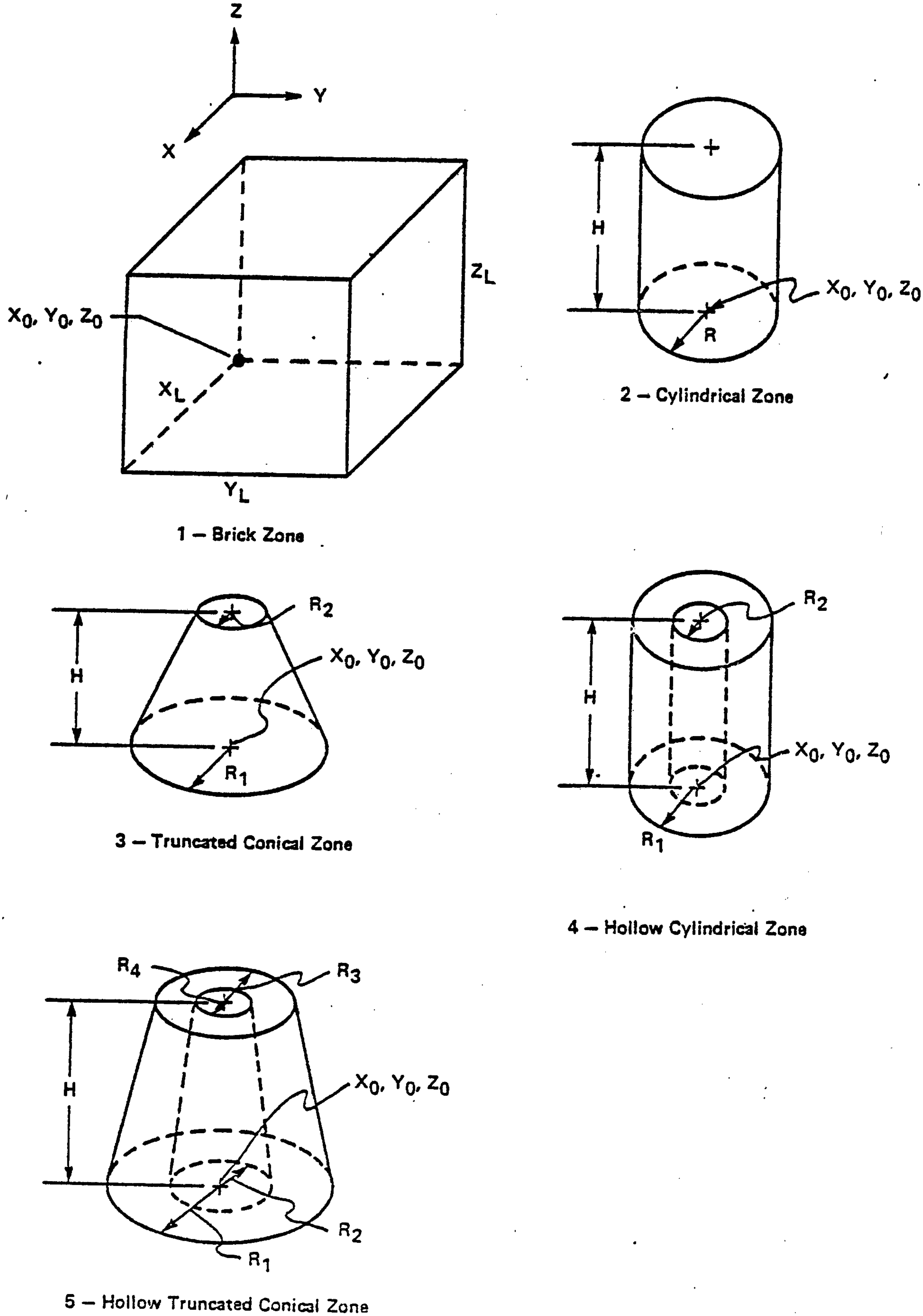

Figure E1-2: Different zone types.

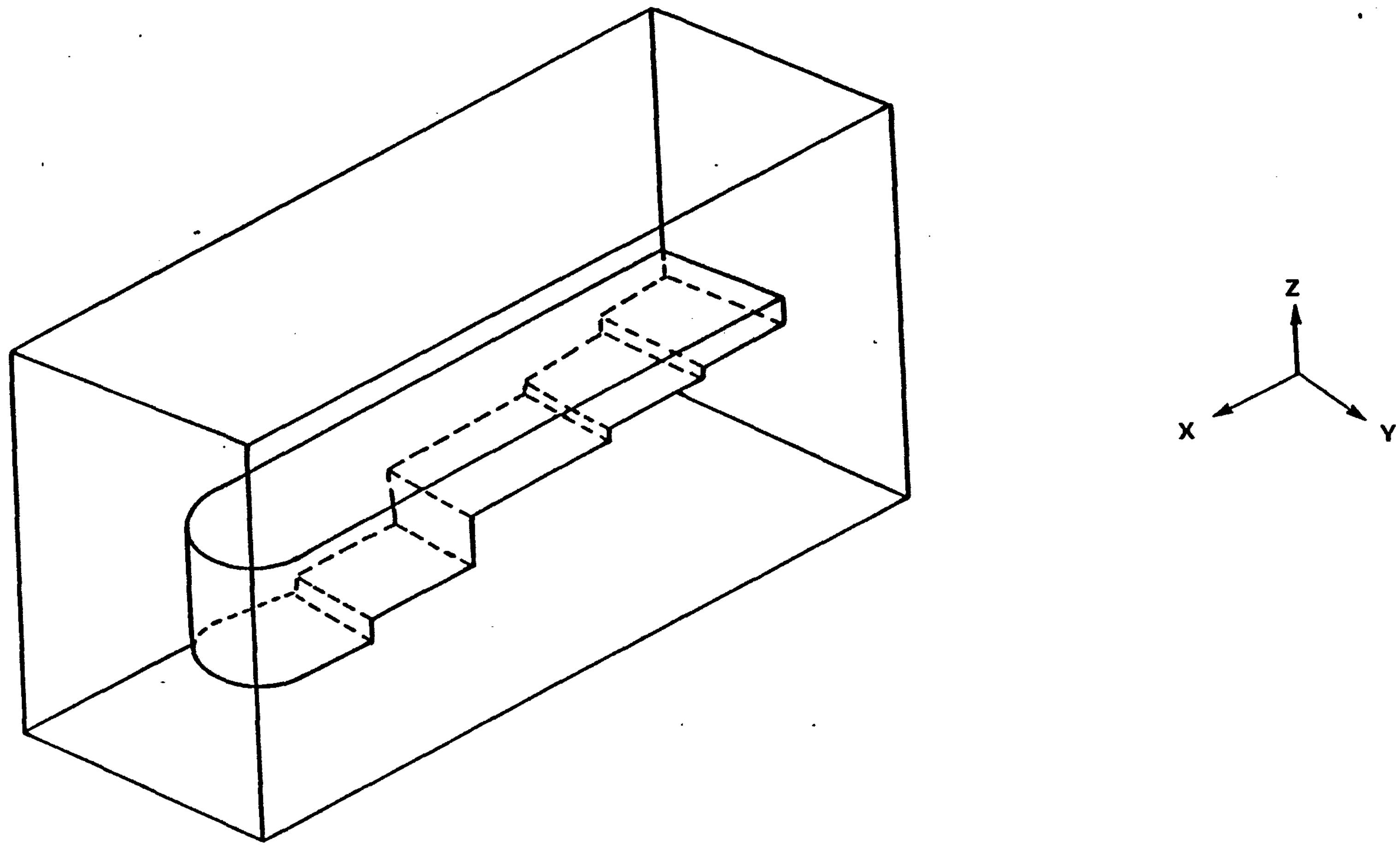

Figure E1-3: Drag portion of test casting model

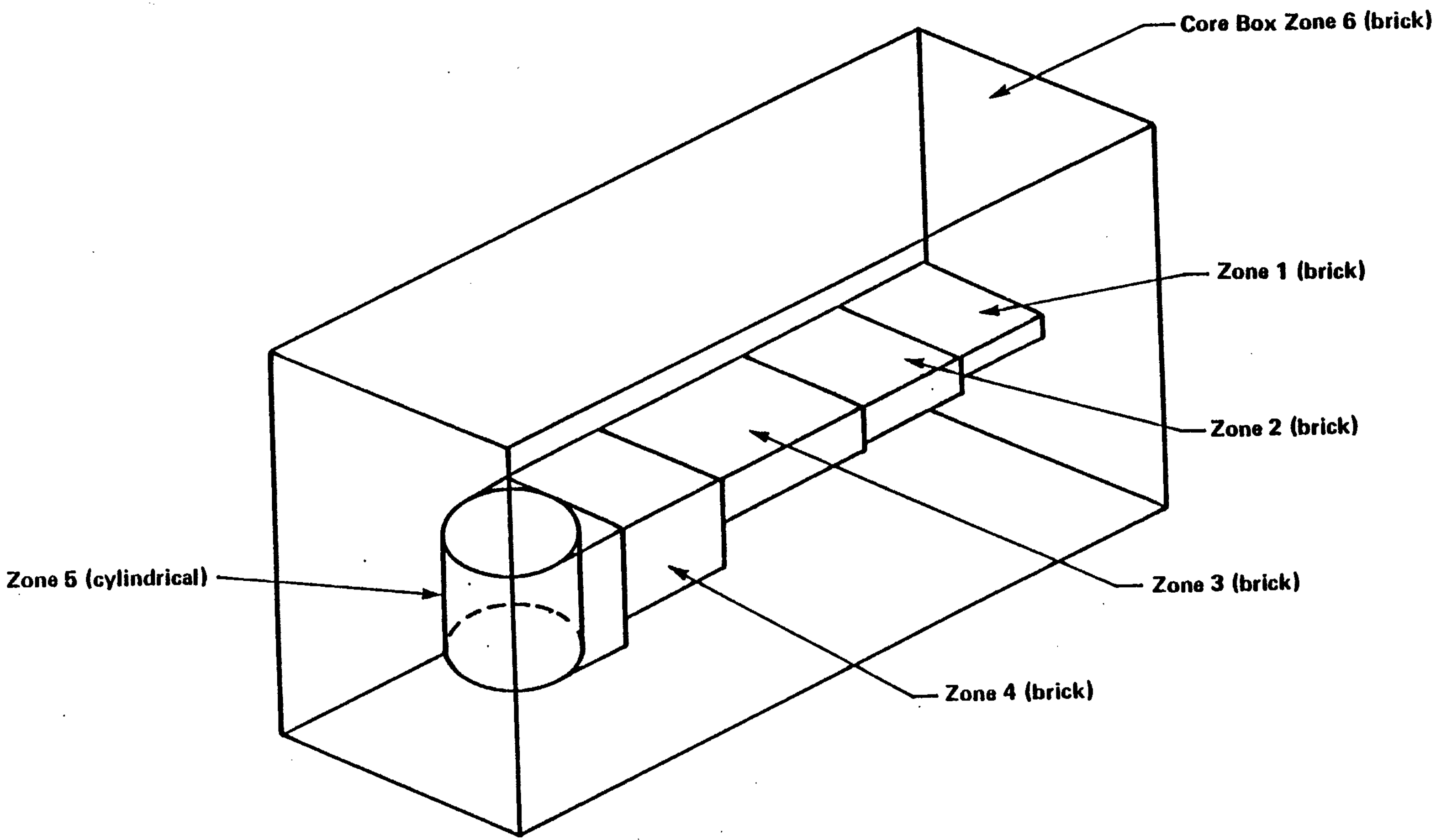

Figure E1-4: Division of the model into zones

To define the geometry of Figure E1-3 the user should:
- Divide the model into a certain number of "zones".
  A zone is the basic building block for the model. To create a model, the user must visualize a subdivision of his casting into zones in a manner similar to that used to manually create a finite-element mesh. Only two zone shapes are available to the user, "brick" and "cylindrical". A brick zone is a volume bounded by six planes. A cylindrical zone is a volume bounded by a cylinder. Figure E1-4 shows a possible way of dividing the model (five brick zones, including the core box, and one cylindrical zone).

E1-2-3 Entering Zone Information

To define the zones of a casting, the DEFINE ZONES command is entered in response to the BCAST Command prompt from the BCAST supervisor. The user must now answer the question "Do you have an existing ZONE file (Y/N)?". The "YES" response would be entered if the user wishes to modify (or simply view) an existing zone file. The "NO" response is used when a new zone file is being created. Next, the "DEFINE ZONES Command" prompt will appear. The nine valid responses to this prompt are described below.

a. CHANGE: The CHANGE command is used to change the dimensions of an existing zone. Zones are referenced by a zone number; since there may be up to 20 zones in one casting, valid zone numbers are 1 through 20. If the user is unsure of a zone number, a summary of all existing zones may be obtained with the TYPE or PRINT commands (see below).

When the CHANGE command is entered, the user will be prompted for a zone number. Then the present dimensions for that zone are displayed at the top of the console. A dimension is changed by moving the highlighted region on the console screen to the dimension to be changed and entering a new value. The highlighted region is moved with the four arrow keys (up, down, right, left). After all desired changes have been entered, the PF4 key is pressed to terminate the CHANGE command and cause the changes to become permanent.

b. ADD: The ADD command is used to add a zone to the casting. When the ADD command is entered, the user is prompted for a zone type. Valid zone types are SAND, BRICK, and S-CYL for the core box, brick, and solid cylinder respectively. Once the zone type is entered, a zone with default dimensions is displayed on the console screen. The user enters the correct

dimensions by moving the highlighted region on the console screen to the dimension to be changed and typing the new value. The highlighted region may be moved with the four arrow keys. The PF4 key is pressed to terminate the ADD command when all new dimensions have been entered.

c. DELETE: The DELETE command is used to delete an existing zone. The user will be prompted for the zone number of the zone to be deleted.

d. TYPE: The TYPE command lists, on the console, a summary of all existing zone types and their present dimensions. This command is useful to verify currently existing zones and the dimensions and zone numbers for each.

e. PRINT: The PRINT command lists, on the printer, a summary of all existing zone types and their present dimensions. This command is useful for getting a hard copy record of the zones.

f. DISPLAY: The DISPLAY command will display all existing zones on the display screen. The user will be prompted for one of the four views which may be displayed: PLAN, SIDE, END, or 3-D. Figure E1-5 shows the coordinate used in each of the four views. The DISPLAY command provides the user with visual feedback for the zones which have been entered.

g. PLOT: The PLOT command is used to obtain a hard copy of the display screen on the X-Y plotter. Since this command copies from the display screen to the X-Y plotter, the view plotted is the view which was last displayed with the DISPLAY command.

h. HELP: The HELP command will list, on the console, a summary of the valid DEFINE ZONES commands.

i. EXIT: The EXIT command terminates the DEFINE ZONES module and returns to the BCAST supervisor. The user is prompted for the name of a zone file to contain the zones in their new (possibly modified) state. The existing zone file (if one was specified when the DEFINE ZONES module was entered) is not altered by any of the above commands. The above commands work with an internal temporary file which is made permanent when the user enters a reply to the "New zone file name" prompt.

E1-2-4 Restrictions

The following restrictions should be taken into consideration before preparing the data describing the castings.

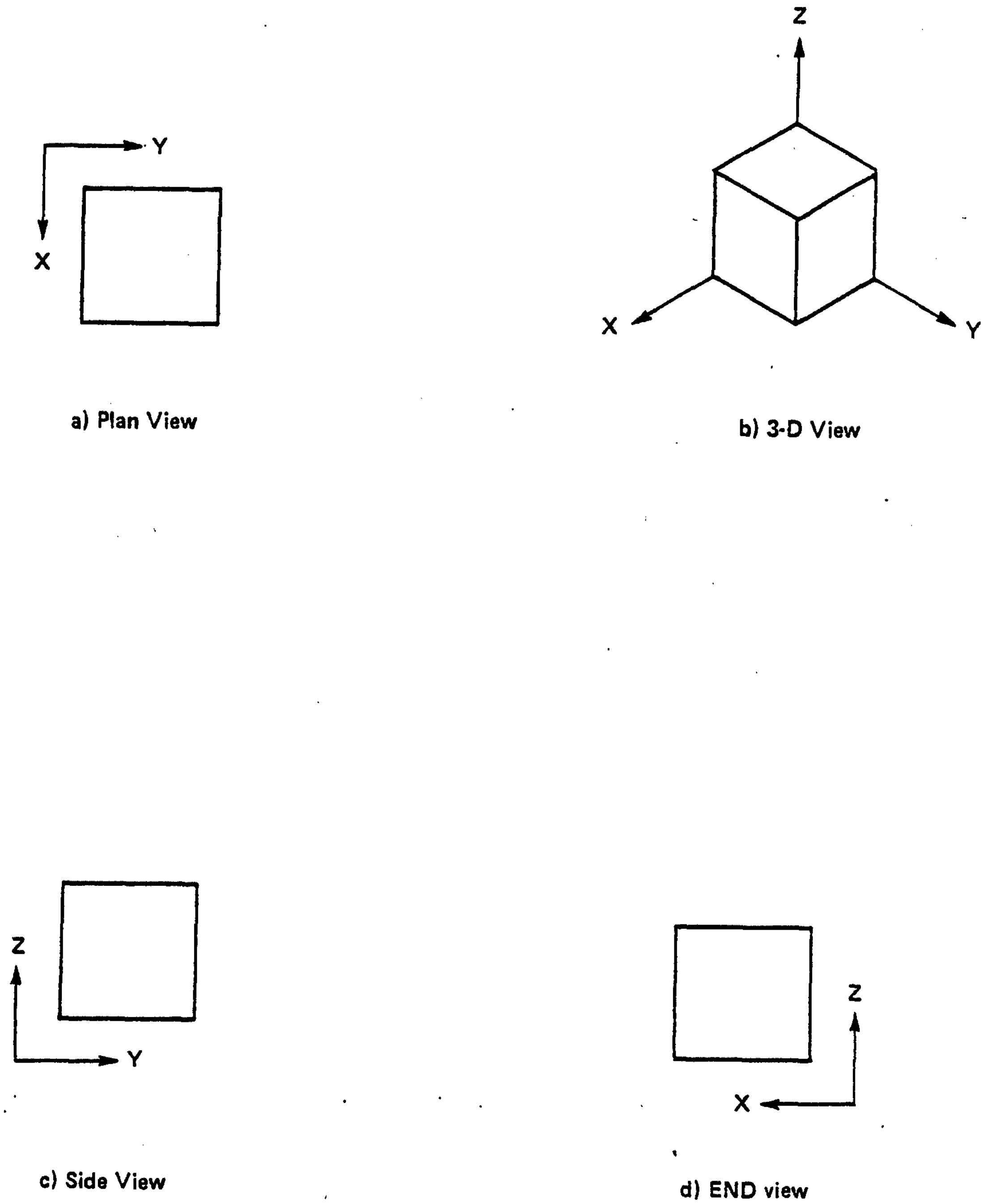

Figure E1-5: Coordinates used for the DISPLAY command

1 - Program BCAST is capable of automatically generating 3-D finite element mesh for castings composed of any combination of brick zones. However, the program (as it stands today) will not generate the mesh for castings that contain more than one cylinder.

2 - In case the casting model includes one cylinder and one or more brick zones the width of the (brick) zone adjacent to the cylinder should be equal to the diameter of the cylinder. The width of other brick zones should be equal to or greater than the diameter of the cylinder. Figure E1-6 shows some examples that BCAST cannot handle, and Figure E1-7 shows some examples for which BCAST would automatically generate a mesh.

3 - The axis of a cylindrical zone (if any) should be parallel to the Z axis.

4 - In the output data file containing the generated mesh data, the nodes are not numbered to give the minimum characteristic (stiffness) matrix band width.

E1-3 AUTOMATIC MESH GENERATION FOR FINITE ELEMENT METHOD

E1-3-1 Summary of Technique

The fundamental concept of the finite element method (FEM) is that any continuous quantity, such as temperature, pressure or displacement, can be approximated by a discrete model composed of a set of piecewise continuous functions defined over a finite number of subdomains. The discretization of the domain into subregions is the first of a series of steps that must be performed when solving a problem using FEM. Unfortunately this particular step does not have a theoretical basis. It is an art and depends on the use of engineering judgement. The application of poor or improper judgement will produce inaccurate results even though all of the other steps are rigorously adhered to. The discretization of the domain involves the decision as to the number, size and shape of subregions (elements) used to model the real body. Engineers are faced with two major problems:

a. The delicate balance of making the elements small enough to give the usable results and yet large enough to reduce the computational effort. The engineer must have a general feeling of what the final values will be so that he can decrease the element size in the areas where the desired result may vary quite rapidly, and can increase it in regions where the desired results are relatively constant.

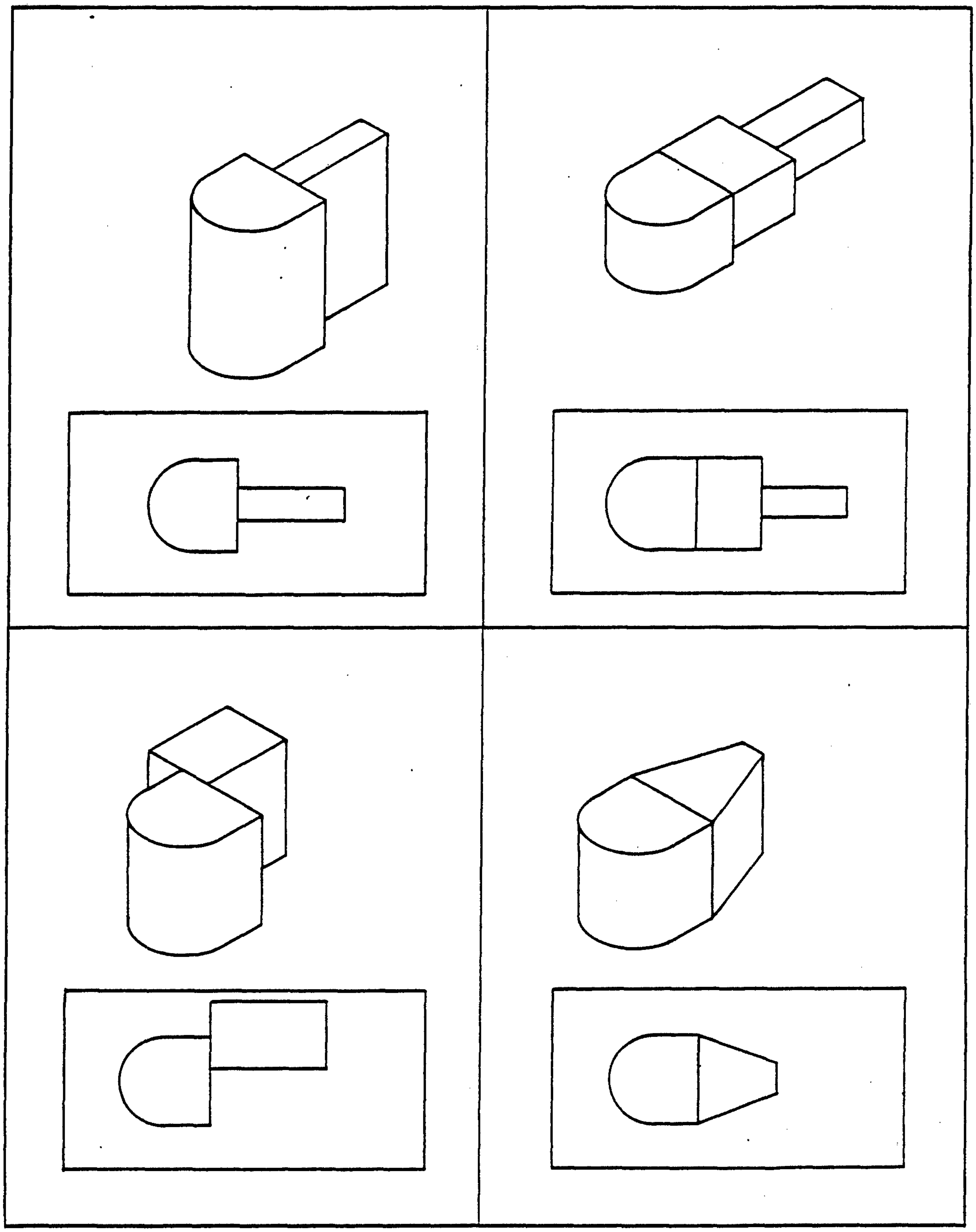

Figure E1-6: Castings which BCAST cannot presently handle

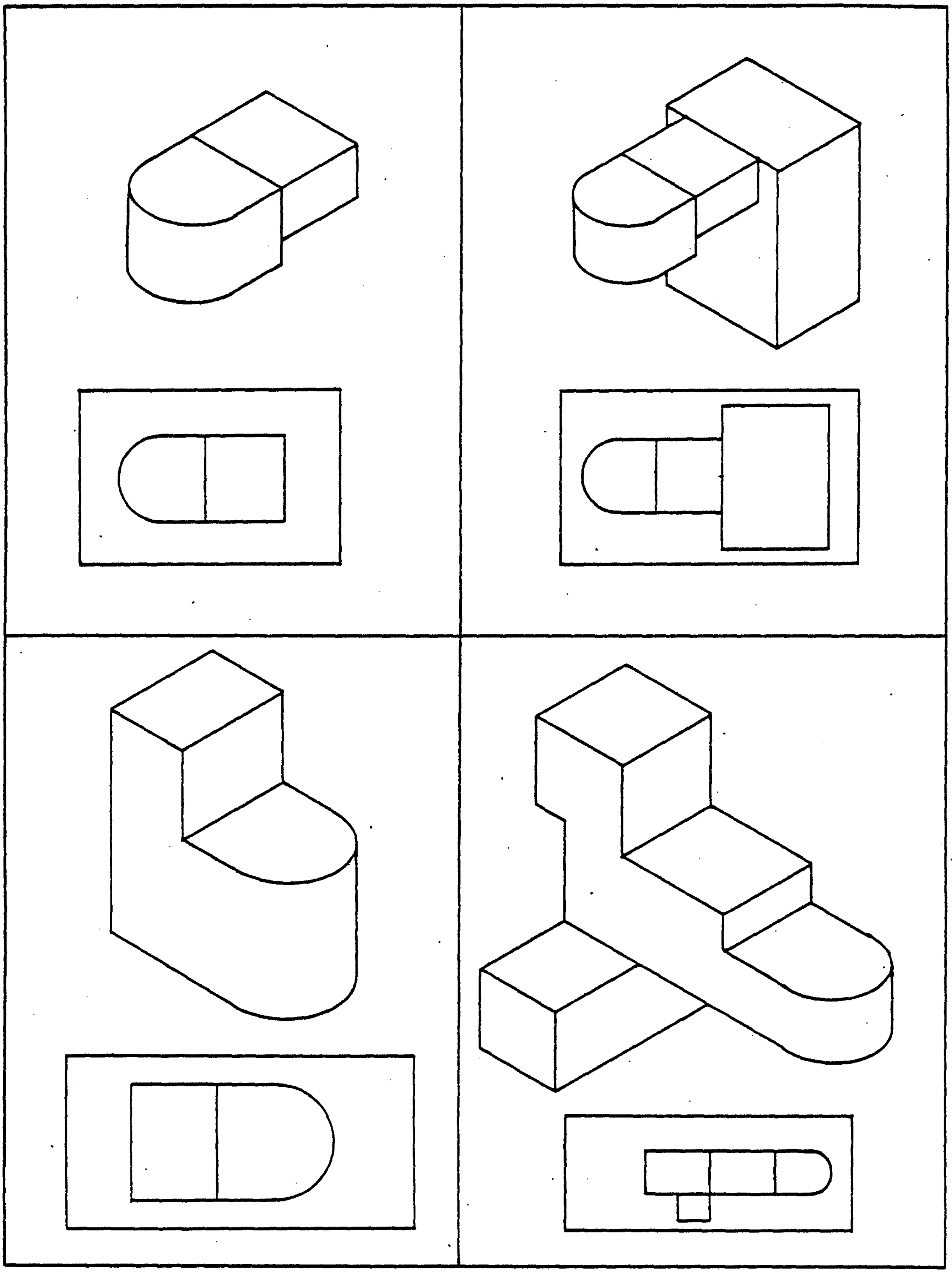

Figure E1-7: Castings which BCAST can handle

b. The preparation of this input date. If done manually, i.e., by punching cards, could be very tedious and subject to human error.

From the previous discussion it seems advantageous to automate this process. However, to tackle the first problem, the automatic mesh generator program should contain a logic to make that decision automatically or with a minimal interaction from the user.

Since the main goal of this project is to study the heat transfer between the molten metal of sand castings and the surrounding sand (flask or core box), the logic as how to organize the elements or subregions of the domain (finer at certain parts and coarse at other parts) was advised. The idea here is to have a finer mesh in the regions describing the contact between the metal and the sand. In order to achieve that, Program BCAST automatically enlarges and reduces the original input geometry, generating two classes of surfaces, inner, in the metal and, outer, in the sand. Figure E1-8 explains this idea for generating a mesh for a brick zone. As shown the program will automatically generate more elements around the boundaries and smaller elements at the corners. Figure E1-9 shows a mesh generated automatically for a cylindrical zone.

Program BCAST automatically generates FEM mesh for sand casting, a layer by layer, i.e., X-Y plane with a delta height ΔZ obtained automatically from the X-Z or Y-Z projection plane of the model. The program also identifies the metal nodes from the sand nodes, identifies the types of the generated elements whether brick or wedge, numbers the nodes and elements, and generates the X, Y, Z coordinates of each node. All of these generated data are then stored in data file to be used later by the finite-element analysis programs of mold heat flow, fluid flow, and stress analysis to provide for castings soundness.

E1-3-2 Types of Elements

Program BCAST generates a finite element mesh composed of two types of elements, brick and wedge elements. Figure E1-10 shows the two types of elements.

As shown in Figure E1-10, the brick element is defined using 8 nodes, numbered clockwise. The wedge element is defined using 6 nodes, numbered clockwise.

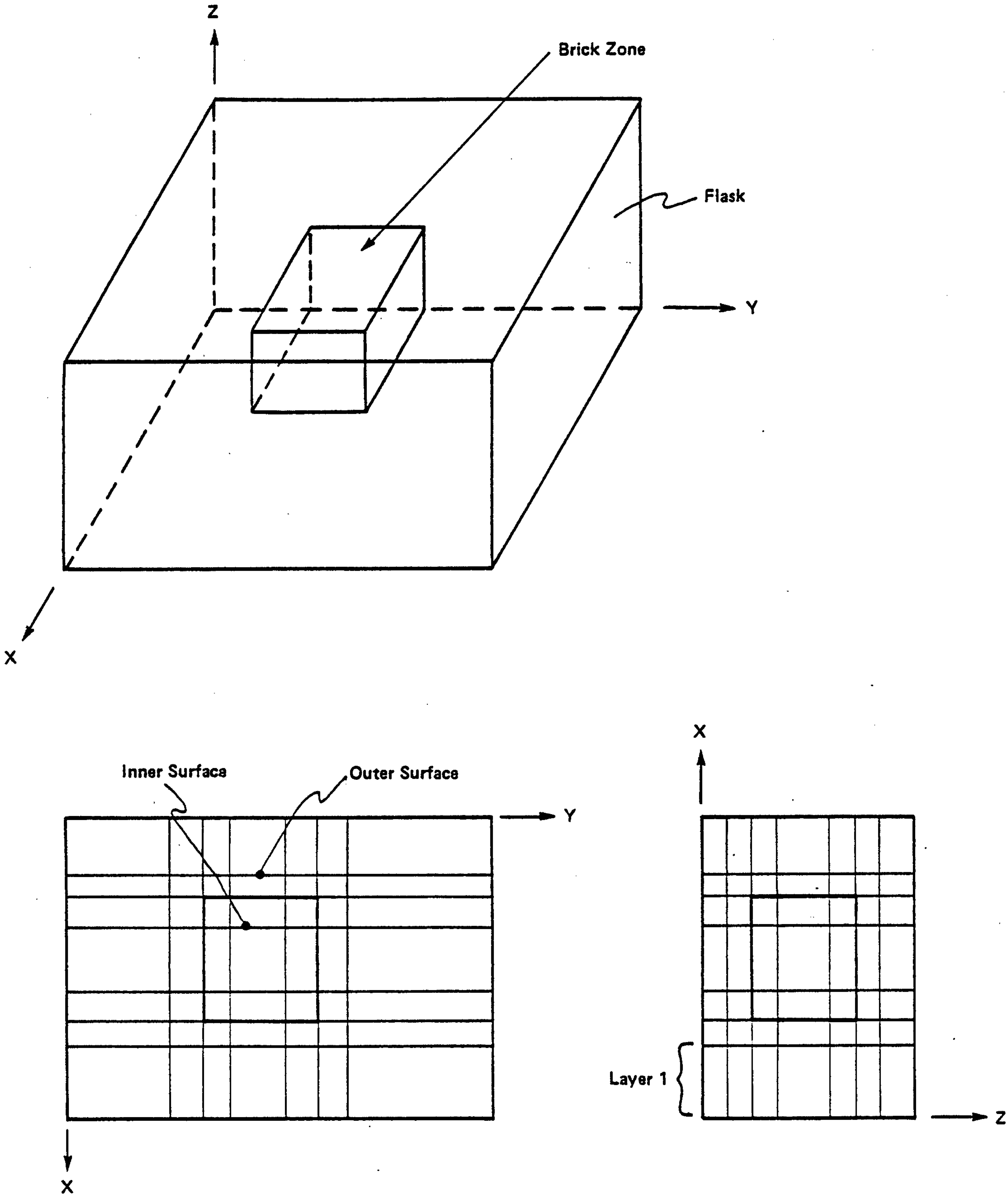

Figure E1-8: Projection of a mesh for a brick zone

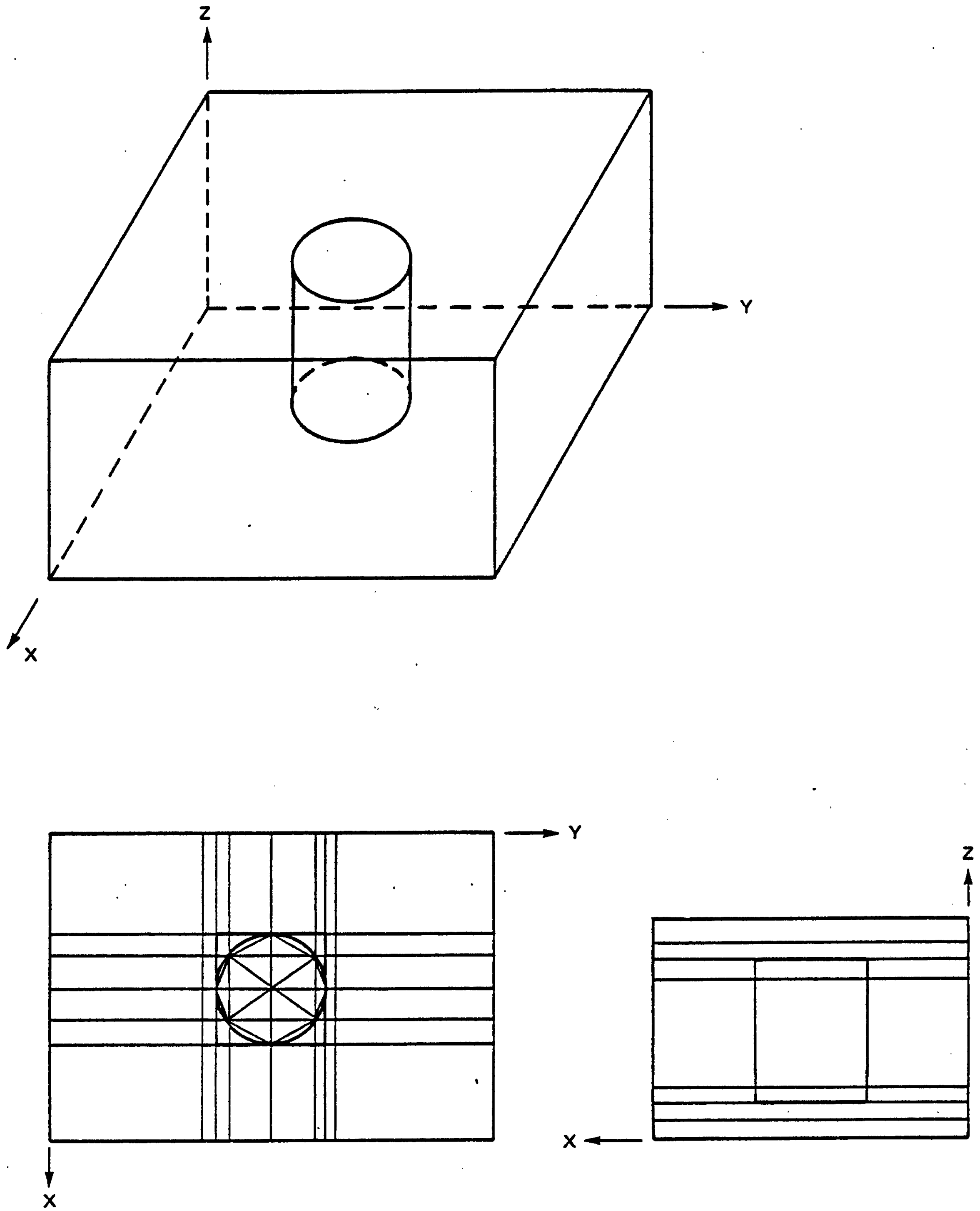

Figure E1-9: Projection of a mesh for a cylindrical zone

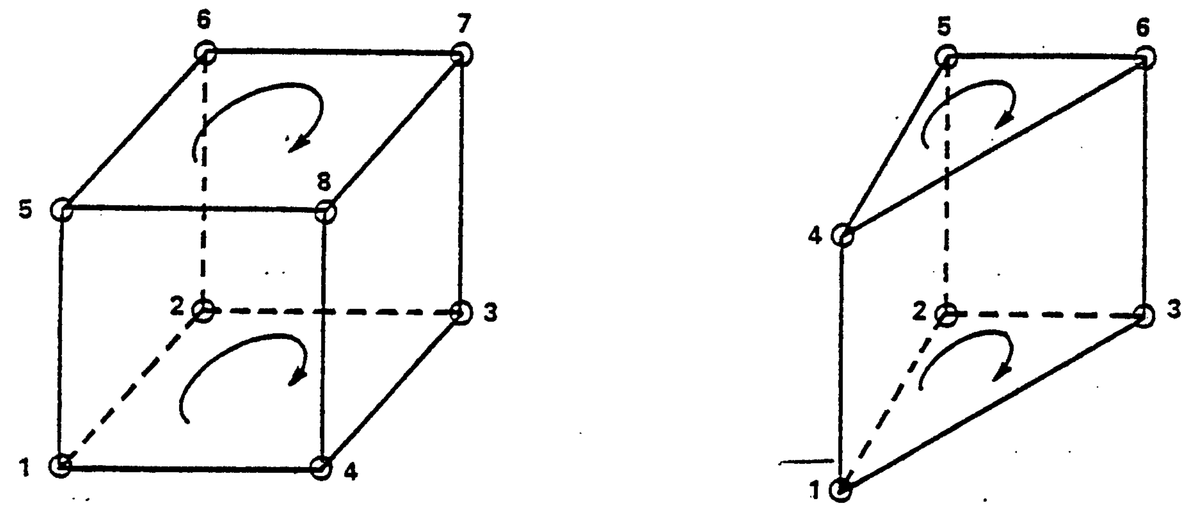

Figure E1-10: Brick and wedge elements.

E1-3-3 Viewing the mesh

To examine the mesh information contained in a mesh file enter the VIEW MESH command in response to the "BCAST Command" prompt from the BCAST supervisor. The user will now be prompted to "Enter the MESH file name". Once the mesh file name has been entered, the "VIEW MESH Command" prompt will appear. Valid responses to this prompt are described below.

a. TYPE: The TYPE command will list, on the console, the coordinates for each node and the node number for each element in any layer. The user will be prompted to "Enter the layer number to be listed". Layers are numbered consecutively, increasing in the positive Z-direction.

b. PRINT: The PRINT command is the same as the TYPE command except that the listing is sent to the line printer rather than the console.

c. DISPLAY: The DISPLAY command will display, on the display screen, the core box and all of the elements for one layer. The elements appear on the screen consecutively starting with the lowest numbered element. The user is prompted for the layer number to be displayed.

d. PLOT: The PLOT command is used to obtain a hard copy of the display screen on the X-Y plotter. Since this command copies from the display screen to the plotter, the layer plotted will be the layer which appears on the display.

e. HELP: The HELP command will list, on the console, a brief description of the valid responses to the "VIEW MESH Command" prompt.

f. EXIT: The EXIT command terminates the VIEW MESH module and returns to the BCAST supervisor.

E1-4 COMPUTER-AIDED DESIGN WITH SECTIONS

This module has been developed to provide the facilities for manipulating cross sections and performing design calculations pertaining to casting process design. CADSEC provides the framework for handling and displaying cross-sectional geometry as well as calculating geometric parameters.

E1-4-1 Files for CADSEC

CADSEC makes use of two types of files.

a. Data files. These are files that are used to enter cross-sectional information to CADSEC. They are usually created by the system editor and are coded in ASCII. CADSEC expects these files to have the extension ASC.

b. Section files. These are random access files created by CADSEC. An existing file may be specified to CADSEC for redisplay and further work. All data files are converted into section files on input to CADSEC.

E1-4-2 Use of Function Buttons

CADSEC makes use of a function button keyboard. This device facilitates selection of frequently specified operations. Each key is labeled as shown below. At any given time, active keys are lighted.

DGTZSC	PLTDSP	EDITSC	VIEW3D
CALCPR	AUXFUN	LBSRCH	NCMCHN
ACCEPT	NEW-SET	NEXT	AGAIN
END	ALL	DELETE	EXIT

The eight keys on the upper half are used to activate one of the eight major system functions. The eight lower keys, together with the light pen, facilitate user interaction. Descriptions of the 16 function buttons follow.

DGTZSC: Activates the cross-section digitizing subsystem. The user can enter new sections via the digitizer tablet.

PLTDSP: The contents of the graphics screen is copied to the X-Y plotter.

EDITSC: Edit Sections. This function provides the facilities for graphical editing of cross-sectional data. Sub-functions such as moving, scaling, rotating, copying, mirroring are available.

VIEW3D: Activates the display management subsystem. Display orientation, display size, number of displayed entities can be changed.

CALCPR: Activates the subsystem for performing casting process design calculations on cross sections.

AUXFUN: Activates interface to other "Design Analysis" programs. Not implemented in Phase I.

LBSRCH: Activates library search subfunction. This will enable designers to search through existing designs for cross sections similar to the one being worked on. In addition, frequently used shapes can be stored and recalled to minimize time and effort required to define a new geometry. Not implemented in Phase I.

NCMCHN: Activates subsystem for generation of cutter paths for NC machining. Will be the last module to be implemented. Not implemented in Phase I.

The following keys are assigned for user interaction.

ACCEPT: An item (cross section) identified by the light pen is selected for operation. For example, in EDITSC mode, a set of items to be scaled are first picked one by one by the light pen. The ACCEPT button is used to add each item to the set.

NEWSET: Clears the set of ACCEPT'ed items.

NEXT: Used to proceed to the NEXT step of an operation. For example, the LBSRCH module uses this key to display the NEXT frame of items from the file being searched.

AGAIN: Used to repeat a previously defined operation.

END: Used to signal the END of data entry operations.

ALL: A special case of ACCEPT. All displayed items are added to the set that will be operated on. For example, if all cross sections were to be scaled to observe the effects of shrinkage, ALL button would be used prior to executing the scaling function.

DELETE: Used to delete items from the design.

EXIT: Used to EXIT from subfunctions as well as for terminating CADSEC.

E1-4-3 Description of Input to CADSEC

Input from ASCII coded data files is recognized in a number of different formats. The first line of all data files is to contain the format type number and header information.

a. Format Type 1:

First line: 1, Header information (I5, 75A1); Subsequent lines, for each cross section:
Surface Type, coefficients of plane equation in format (I5, 5X, 4F10.3).
Points defining the cross section, X(1), Y(1), Z(1), R(1) one set per line in format (4F10.3). There can be a maximum of 25 points per section. Sections are delimited by an X(1) value greater than 9999.9 inches. R(1) is the radius associated with the input point.
Surface type variable (ISTYP) defines the form of the plane equation to use with the cross section. These are:
ISTYP = 1 for x = f(y,z)
ISTYP = 2 for y = f(z,x)
ISTYP = 3 for z = f(x,y)

If ISTYP = O, the system determines ISTYP by using the first three points of the cross section. Figure E1-11 and Table E1-2 illustrate an example cross section and its data set.

b. Format Type 2:

Other format types can be added as required. Format Type I has enough flexibility to handle most Phase I requirements.

E1-4-4 Description of DGTZSC

This module provides for entry of cross sections via a digitizer tablet. A section is entered by digitizing a sufficient number of points. As points are digitized, the results are displayed on the screen. The coordinates of the digitizer cursor are continuously displayed on the screen as an aid in picking up particular coordinates.

E1-4-4a Control Functions:

Z: Located on the digitizer cursor. Causes the entry of a point.

END: Located on the digitizer cursor as well as the function button box, terminates the entry of a section.

CLOSE: Located on the digitizer cursor, closes the cross section and terminates entry.

DELETE: Located on the function keyboard, deletes the last digitized point.

EXIT: Located on the function keyboard, causes exit from DGTZSC mode.

E1-4-4b Digitizing Functions:

The following functions are provided to facilitate the entry of more common shapes such as arcs of circles. These are selected via the menu on the left side of the digitizer tablet. The description of these functions follows:

CHANGE: DGTZNG Lets the user change digitizing parameters; namely the scale factor of the figure to be digitized.

PRMTRS: CIRCLE Facilitates the entry of a circle by digitizing its center and a point on its circumference.

TABLE E1-2. ASCII File Example In Format Type I

```
1, EXAMPLE DATA SET IN FORMAT TYPE 1
0, 0.0, 0.0, 1.0, 0.0
-1.5, 0.2, 0.0, 0.0
-1.4, 1.8, 0.0, .250
-0.9, 1.4, 0.0, .250
-0.9, 0.6, 0.0, .500
1.0, 0.6, 0.0, .375
1.0, 1.2, 0.0, .375
2.2, 1.2, 0.0, .375
2.3, 0.2, 0.0, 0.0
2.2, -1.0, 0.0, .375
-1.4, -1.0, 0.0, .375
-1.5, 0.2, 0.0, 0.0
```

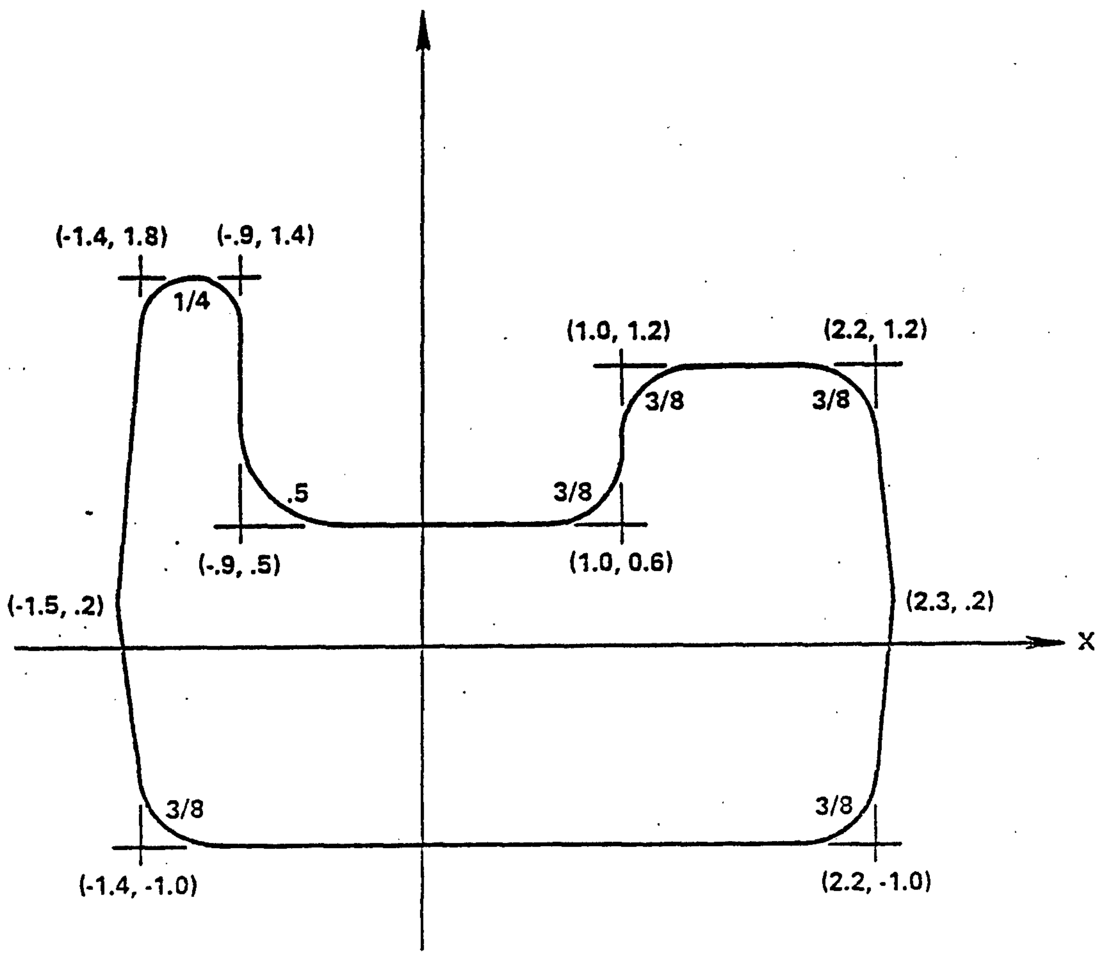

Figure E1-11: Casting Cross Section Example

CENTER RADIUS	Facilitates the entry of a circle by digitizing the center and entering the radius on the keyboard.
CIRCLE THREE POINTS	Facilitates the entry of a circle by digitizing three points on its circumference.
ARC THREE POINTS	Facilitates the entry of an arc of a circle.
B-SPLN	Facilitates the entry of a smooth curve by digitizing a few points. Points are automatically generated via B-Spline functions.
MIRROR X-AXIS	Mirrors the figure being digitized in the X-direction, around its last point.
MIRROR Y-AXIS	Mirrors the figure being digitized in the Y-direction, around its last point.
MIRROR X-&-Y	Mirrors the figure being digitized both in the X and Y directions, around its last point.

Other menu selections can be added as required.

E1-4-5 Description of PLTDSP

This function copies the contents of the graphics screen to the X-Y plotter.

E1-4-6 Description of EDITSC

Provides facilities for graphical editing of sets of cross sections. User interaction is via the light pen and function buttons. The following menu functions are provided on the left side of the graphics screen.

MOVE: Move a set of sections to another location. This translation can be achieved by:

1. Entry of the desired offsets via the keyboard or,
2. Attaching the set to the cursor and dragging them to the new location on the graphics screen.

SCALE: Scales a set of sections. Scale factors are entered from the keyboard. Scaling can be performed around:

1. The origin.
2. The center of the set.
3. A specific point.

ROTATE: Rotates a set of sections. Rotation angles are entered from the keyboard. Rotation is performed around:

1. The origin.
2. The center of the set.
3. A specific point.

COPY: Copies a set of sections.

MIRROR: Generates a mirror image of a selected set of sections. The options are:

1. Mirror along X-AXIS.
2. Mirror along Y-AXIS.
3. Mirror along Z-AXIS.
4. Mirror along A-LINE.

CLIP: Clips and displays only that portion of a set of items that reside inside a specific rectangle. The rectangle is entered by digitizing its lower left hand corner and its upper right hand corner.

SMOOTH: Smooths a cross section by fitting B-spline curves.

ADD-PTS: Adds points to a selected cross section at any desired location. Not fully implemented.

DEL-PTS: Delete points. Deletes selected points of a cross section. Not fully implemented.

HIDE: Hides selected sections from view. Helps in management of a crowded screen.

SEEK: Opposite of HIDE. Scans through hidden sections. Selected sections are restored to the screen.

E1-4-7 Description of VIEW3D

Provides facilities for overall management of the three-dimensional display for the CAD system.

ZOOM-IN: Recalculates the display mapping function to provide the zooming-in effect for the area specified by the user via the cursor.

ZOOM-OUT: Recalculates the display mapping function to provide a zoom-out. The zoom-out factor is entered via the keyboard.

ROTATE: Display viewing angles are input via the keyboard.

NEW VIEW: Display the present contents of the screen according to the new display parameters.

VIEW SCTNS: Displays only the selected set of sections according to the new display parameters.

RESTORE: Lets the user restore the display to a new view that includes all sections.

E1-4-8 Description of CALCPR

Provides facilities for calculation of geometric properties of cross sections. Casting design calculations will also be implemented in this module.

PERIMETER: Calculates perimeters of cross sections and types them out.

AREA: Calculates cross-sectional areas and types them out.

CENTROID: Calculates the centroid of cross sections and types them out.

CIRCLES: Positions circles at selected locations on cross sections to help view metal flow. Options include:

1. CNTR+R: Define a circle by digitizing its center and a point on its circumference.
2. 3 POINTS: Define a circle by digitizing three points on its circumference.

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EXHIBIT 2

CASTING SOLIDIFICATION SIMULATION PROGRAM: CSSP

DOCUMENTATION
PHASE I

FOREWORD

CASTING SOLIDIFICATION SIMULATION PROGRAM: CSSP

The exhibit describes (a) the approach used in preparing a finite element program for simulating the heat flow during solidification of a casting in a sand mold (CSSP) and (b) the procedures to be followed in using the program. Also described are routines for preparing the input to CSSP and post processing routines for presenting and analyzing the output of CSSP

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E2-1 INTRODUCTION

The Casting Solidification Simulation Program (CSSP) is a computer program designed to simulate the heat transfer behavior during freezing and the subsequent cooling of an arbitrarily shaped 3D casting solidifying in a sand mold. The analysis is based on the finite element method and includes the consideration of the release of latent heat of fusion as the alloy cools through the freezing range from liquidus to non-equilibrium solidus. CSSP is designed to be used with a package of computer assisted design and simulation routines - CAD/CAM CASTING PROCESS - for the design by foundrymen of the rigging (risering and gating) of complex casting geometries and the subsequent evaluation of the design by simulation of the freezing process.

In preparation for the use of CSSP to simulate the freezing of a casting, a geometric description of the mold cavity and the flask must be prepared; the goemetry must be subdivided into nodes and elements for the numerical analysis; the thermal properties and initial temperatures must be assigned to the elements of the sand and alloy, and a timestep selected. The simulation will yield a data file of temperatures at each of the nodes for each of the timesteps. The output data of CSSP may be voluminous. Thus, several routines have been developed for examining or postprocessing the thermal data to allow making the decisions necessary for evaluating the design. These include the ability to make plots of cooling curves, cooling rates, temperature profiles, temperature gradients, and freezing patterns.

For those interested in gaining familiarity with CSSP by using the routines a brief documentation and set of instructions are included as Appendix A to this report and an updated version is included as part of the program tape as file CSSP.DOC. A better understanding of the working and assumptions of the program may be obtained by reading the chapters of the manual that follow.

Chapter 2 gives a brief review of the literature on simulation of heat flow in castings.

Chapter 3 reviews the general procedure of the finite element method used with CSSP and specifies the assumptions made in the analysis.

Chapter 4 illustrates the use of AGRID to prepare an input data file.

Chapter 5 discusses the use of CSSP on a sample problem.

Chapter 6 illustrates the use of the post processing routines.

Appendix A, as mentioned, gives a brief documentation, set of instructions, for use of CSSP, AGRID, and the output routines.

Appendix B describes calculations that were made to test the validity of the techniques of CSSP.

E2-2 GENERAL BACKGROUND

There have been several attempts to simulate the solidification of castings. One of the earliest to study solidification and simulate it was Paschkis (1) who used electric analog methods. This involved building an electric circuit to represent the thermal conditions of the casting problem. The electric analogy results had to be converted to heat transfer quantities before the results could be compared to the results of direct experimentation. Thus, voltages were converted to temperatures and electrical currents were converted to heat flows. Simulating the solidification of 0.2 per cent carbon steel, Paschkis found the thickness of steel solidified as a function of time, and he found temperaturetime relationships for the casting problem. In this simulation, Paschkis used an artificially raised specific heat to account for the heat of fusion. Next, Paschkis(2) studied the influence of properties on the solidification of metals. Using his electric analog method, Paschkis varied the thermal conductivity, specific heat, heat of fusion, and solidification range of steel. By demonstrating that the variation of properties can change solidification times, Paschkis has shown that accurate thermal properties are needed for accurate simulations of metal solidification.

Mizikar(3) modeled heat flow in continuously cast steel slabs. Using a onedimensional finite difference technique, he developed temperature and solidification profiles of the slabs. Lait, Brimacombe, and Weinberg(4) also developed a onedimensional finite difference heat transfer model for continuously cast steel. In their model, the latent heat was considered as a heat source through the solidification range, and the thermal conductivity of liquid regions was raised to account for convective mixing. The results were given in terms of temperature field and pool profiles.

Stoehr and Brody (5,6) developed a two-dimensional implicit finite difference model to simulate the solidification solidification of large steel roll castings. The results were graphically represented with liquidus and solidus fronts drawn on the casting. In the simulation, the latent heat was considered in the sensible heat. The sensible heat was then used to calculate heat capacitances at different temperatures.

Weatherwax and Riegger(7) simulated the solidification of die cast aluminum pistons. They developed a three-dimensional finite difference heat transfer model. The latent heat was represented by the release of the heat of fusion at the midpoint of the solidification range.

Also, working with aluminum, Jevarajan and Pehlke(8) used a two-dimensional finite difference analysis to simulate the solidification of castings with chills. Marrone, Wilkes, and Pehlke(9,10) modeled the solidification of "T" shape and "L" shape low carbon steel castings. Their approach consisted of a two-dimensional finite difference technique utilizing an artificially raised heat capacitance to account for the heat of fusion. The main accuracy limitation for them was the lack of reliable thermal data for sand and steel at high temperatures. Moreover, Pehlke, Kirt, Marrone, and Cook(11) simulated the solidification of

silicon brass and aluminum castings with a two-dimensional explicit finite difference method. Heat flow and temperature distribution during the solidification of castings were numerically computed, using a finite difference scheme, by Davies, Stokke, and Westby(12).

Most of the work on casting has centered on the finite difference method. Today, some people are looking at the finite element method. Das(13 has advocated the flexibility and versatility of the finite element method if it is applied to the design of castings. Essentially, solidification is a transient nonlinear heat conduction problem. In the area of nonlinear heat conduction, Orivuori(14) developed a finite element method simulation to consider nonlinearities arising from temperature dependent thermal properties. His model was demonstrated for a heat conducting bar. Bruch and Zyvoloski(15) used the finite element method to simulate transient two-dimensional heat conduction with linear and nonlinear considerations. Their work was applied to the heat conduction of a rectangular bar.

Comini, Del Guidice, Lewis, and Zienkiewicz(16) examined nonlinear heat conduction with a special reference to a change of phase. Here the latent heat was incorporated as rapid variations of the heat capacity in the solidification range. Their work was tested on a solidifying infinite slab of liquid and on the solidification of a liquid in a corner region. Furthermore, Morgan, Lewis, and Zienkiewicz(17) developed a more numerically stable finite element solution to heat conduction problems with a phase change. They incorporated the heat of fusion into the enthalpy. By using a smooth enthalpy curve to formulate their equations, they were able to avoid numerical instabilities introduced by using a heat capacitance curve with a sharp peak. There are also commercially available general purpose programs like ANSYS(18) to perform finite element heat transfer analysis. The accuracy of using finite element method solutions to the transient heat conduction equation was verified by Donea(19) and Cella (20) . Thus, there seems to be a good indication that the finite element method can be successfully used to simulate heat flow in castings.

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E2-3 FINITE ELEMENT APPROACH

The objective of CSSP and related programs is to conveniently simulate the heat transfer during freezing of a casting in an insulating mold. While the programs have considerable generality, the specific objective of Phase I has been to develop routines to simulate the freezing of a particular alloy and mold combination, that is cast armor steel and nobake (phenolic bonded) silica sand. Due to the general nature of the problem and the particular armor steel/nobake sand combination, certain assumptions and design simplifications have been made. A variety of complex 2D and 3D geometries may be simulated by these routines. It is important, however, to be aware of the assumptions made in the design of the program, particularly with the handling of material properties. These are outlined below.

E2-3-1 Description

CSSP uses the finite element method to approximate the heat flow. This numerical method is based on subdividing the geometry into many small three-dimensional elements that have shapes like the ones in Figure E2-3-1. The subdivision may contain any combination of tetrahedorns, wedges, and hexahedrons. CSSP converts all wedges and hexahedrons to tetrahedorns prior to the simulation. The points at the corners of the elements are called nodes. The elements are assumed to have linear temperature distributions where the temperature at a point is a function of the position of the point. Thus, for a tetrahedron

$$\text{Temp} = a_1 + a_2X + a_3Y + a_4Z \qquad (3\text{-}1)$$

where the a's are constants for each element. From this equation, one sees that the temperature distribution across each element isllinear. Additionally, the temperatures at nodes shared by more than one elemnt must be identical. Hence, CSSP is analyzing a continuous function (temperature) with a discrete model described by a set of piecewise continuous functions in the elements. The wedges and hexahedrons have been built from tetrahedrons.

E2-3-2 Equations

The differential equation for heat flow has the form

$$\nabla^2 T = \frac{1}{\alpha} \frac{\partial T}{\partial t} \qquad (3\text{-}2)$$

where K is the thermal conductivity, T is the temperature, α is the thermal diffusivity, and t is the time. By assuming that the parameters are functions of space coordinates, Segerlind (1) creates the following

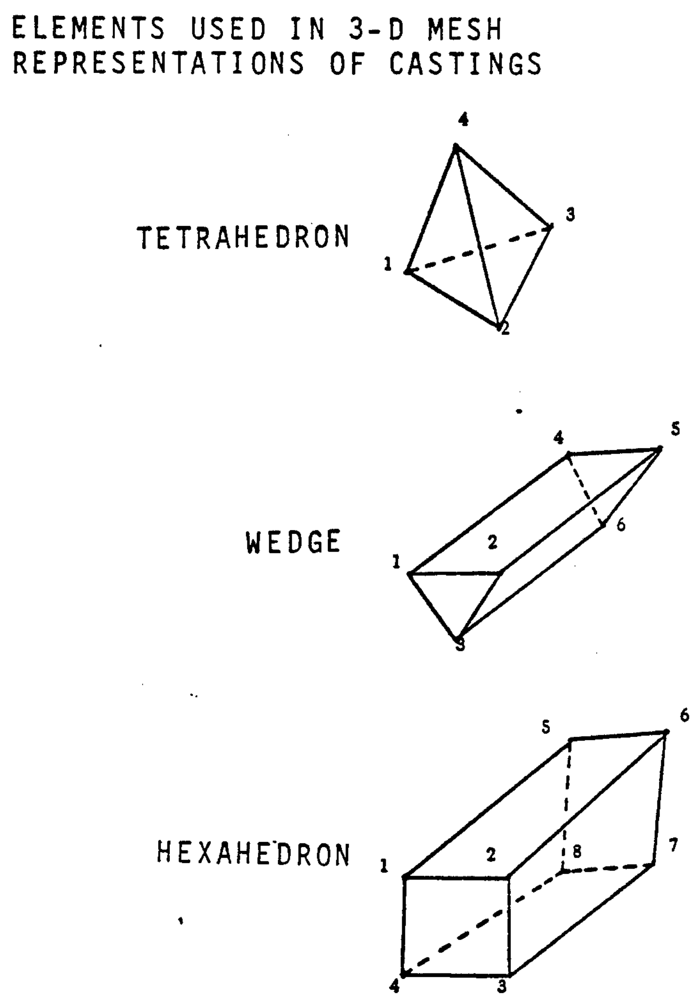

Figure E2-3-1: Elements used in CSSP.

system of equations

$$[C]\,\frac{\partial\{T\}}{\partial t} + [K]\,\{T\} + \{F\} = 0 \qquad (3\text{-}3)$$

where [C] is an xn matrix for n nodes containing the functions of heat capacitance, {T} is a column matrix containing the temperatures for n nodes, [K] is an nxn matrix containing the functions of thermal conductivity and convective boundary conditions, and [F] is a column vector containing the functions of convective boundary conditions, heat flux boundary conditions, and internal heat generation terms. Before this equation is used, a finite difference approach in the time domain is used, a finite difference approach in the time domain is used to obtain a linear equation. The representation of $\partial\{T\}/\partial t$ is the critical step. There are many ways to do this. CSSP assumes that the temperature's time derivative is equal to the change in temperature for one timestep divided by the length of the timestep. That is

$$\frac{\partial\{T\}}{\partial t} = \frac{\{T\}_{t+\Delta t} - \{T\}_t}{\Delta t} \qquad (3\text{-}4)$$

where t is the lenght of the timestep. This equation uses the derivative at the of the timestep for the entire timestep. Also, all materail properties will be evaluated at time t. Thus, the set of equations becomes

$$\frac{1}{\Delta t}\,[C]_t\,[\{T\}_{t+\Delta t} - \{T\}_t] + [K]_t\,\{T\}_{t+\Delta t} + \{F\} = 0 \qquad (3\text{-}5)$$

Rearrangement yields

$$[K]_t + \frac{1}{\Delta t}\,[C]_t\,\{T\}_{t\Gamma t} = \frac{1}{\Delta t}\,[C]_t\,\{T\}_t - \{F\} \qquad (3\text{-}6)$$

There are other assumptons that can be made on the time derivative. Assuming

$$\frac{\partial\{T\}}{\partial t} = \frac{\{T\}_t - \{T\}_{t-\Delta t}}{\Delta t} \qquad (3\text{-}7)$$

uses the derivative for the previous time interval as a derivative used to calculate $\{T\}_{t+\Delta t}$. This leads to

$$[K]_t\{T\}_{t+\Delta t} = \frac{1}{\Delta t}\,[C]_t\,[\{T\}_{t-\Delta t} - \{T\}_t] - {}^3F\}_t \qquad (3\text{-}8)$$

Assuming the derivative can be approximated by the change in temperature over two timesteps, it is

$$\frac{\partial\{T\}}{\partial t} = \frac{\{T\}_{t+\Delta t} - \{T\}_{t-\Delta t}}{2\Delta t} \tag{3-9}$$

The resulting equations are then

$$[\frac{1}{\Delta t} [C] + [K]]_t \{T\}_{t+\Delta t} = \frac{1}{2\Delta t} [C]_t \{T\}_{t-\Delta t} - \{F\}_t \tag{3-10}$$

The last two systems of equations are not self-starting at t=0. The first method was chosen becasue it appears to most accurately reflect the time derivative during the timestep being calculated.

E2-3-3 Computer Program

A flow chart of CSSP is presented in Fibure E2-3-2. The first step of simulation run is to input the required information. Examples of required information are the geometry of the problem, the elements used, initial tempertures, boundary conditions, and material properties. Then, for each timestep stiffnesses must be calculated. In other words, the system of equations must be formulated by processing each element. This procedure is flow charted in Figure E2-3-3. The next thing is to alter the system of equations if there are any nodes specified to remain at a constant temperature. After this is done, the system of equations is solved using a Gauss-Seidel iteration technique. Before the temperatures for the timestep are output, the temperatures may be adjusted as well be described in Section E2-3-4.

E2-3-4 Solidification

The problem being studied involves the solidification of steel. During this solidification, latent heat is given off. There are usually three ways this phenomenon can be handled in a numerical solution. An obvious method is to introduce a heat generation term during the solidification. This method seems difficult becasue the amount of heat generated is a function of the temperature before and after the timestep during which solidification is occuring. Alternately, one could use a virtual temperature for the initial temperature to take into account the heat generated during solidification. Thus, the steel would cool from a higher virtual temperature with no solidification heat generation. CSSP treats solidification with an artificially raised heat capacitance over the mushy zone. In this way the heat generated is equal to the heat capacitance multiplied by the decrease in temperature.

Cooling through the mushy zone with a higher heat capacitance yields a release of energy equal to

$$\Delta EHIGH = CPHIGH\ (TLIQ - TSOL) \tag{3-11}$$

Where CPHIGH is the artificially raised heat capacitance, TLIQ is the liquidus temperature, and TSOL is the solidus temperature. Similarly, cooling through the mushy zone with the normal heat capacitance yields a release of energy equal to ΔENORM .

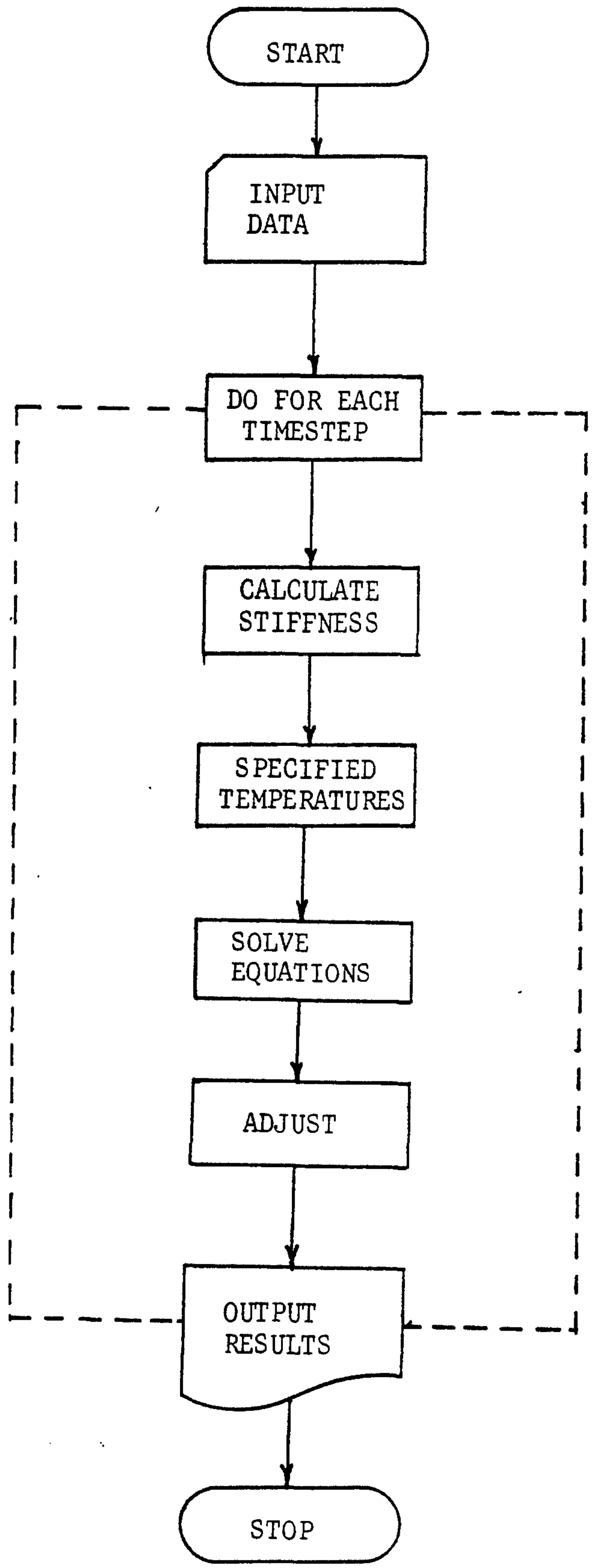

Figure E2-3-2: CSSP flow chart.

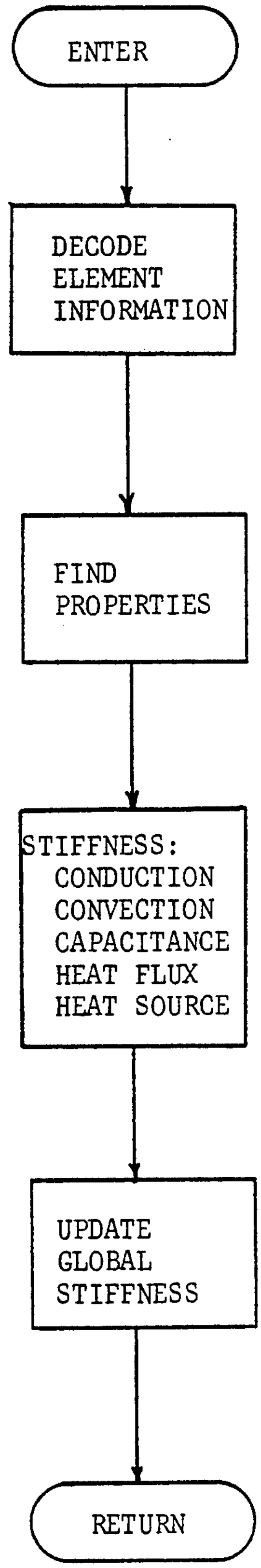

Figure E2-3-3: Stiffness calculation flow chart.

$$\Delta ENORM = CPNORM\ (TLIQ - TSOL) \tag{3-12}$$

where CPNORM is the normal heat capacitance. Furthermore, by choosing a CPHIGH that makes

$$H_f = \Delta EHIGH - \Delta ENORM \tag{3-13}$$

where H_f is the latent heat of fusion, the solidification will have been represented. The value of CPHIGH can be written as

$$CPHIGH = CPNORM + \frac{H_f}{(TLIQ-TSOL)} \tag{3-14}$$

The substitution of typical values for armor steel yields

$$CPHIGH = 0.20 + \frac{126.0}{(2735-2643)} \tag{3-15}$$

$$CPHIGH = 1.57 \tag{3-16}$$

where units are in BTU, lbs, and degrees F. Therefore,

$$CPHIGH - CPNORM = 1.36\ \text{BTU/lb degrees F} \tag{3-17}$$

which indicates that CPHIGH is almost eight times larger than CPNORM. This artificially raised heat capacitance simplifies the simulation by including the latent heat problem with the heat capacitance which is handled easily. Figure E2-3-4 shows the Cp versus temperature presently used in CSSP for armor steel.

This procedure is well defined as long as the temperature lies in one particular zone either solidus, mushy, or liquidus. To simulate solidification more accurately, one must make adjustments to the calculated temperature when it lies in a zone different from its previous zone.

The adjustment routine is flow charted in Figure E2-3-5. Also, the routine's basis on enthalpy can be seen in Figure E2-3-6. The adjustment routine is as follows. Suppose the finite element computation indicates for a node initially in the liquid state at a temperature TOLD = 2800 degrees F that after the timestep it has reached a temperature TNEW = 2680 degrees F. For a steel with a liquidus temperature at 2735 degrees F this indicates a change from the liquid state to the mushy state. Hence, the final temperature must be adjusted. The loss of energy would have been computed on the basis

$$\Delta E = (TOLD - TNEW)\ CPL \tag{3-18}$$

where TOLD is temperature at the beginning of the time interval, TNEW is the unadjusted temperature at the end of the interval, and CPL is heat capacitance of liquid steel. Now, by following the enthalpy line in the liquid region and then down the line in the mushy zone until the same amount of engergy has been lost, we can find the equation

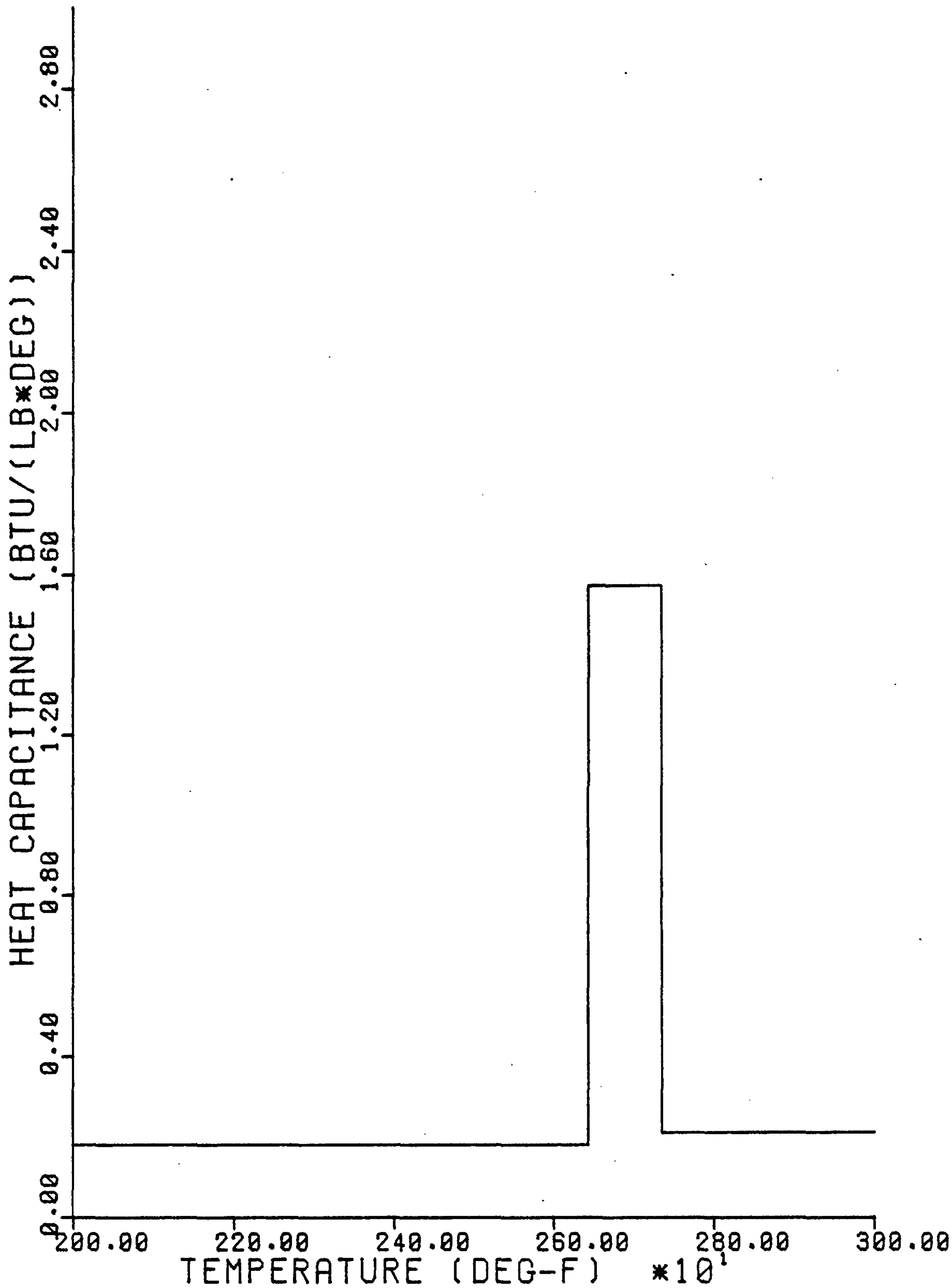

Figure E2-3-4: C_p versus temperature for steel.

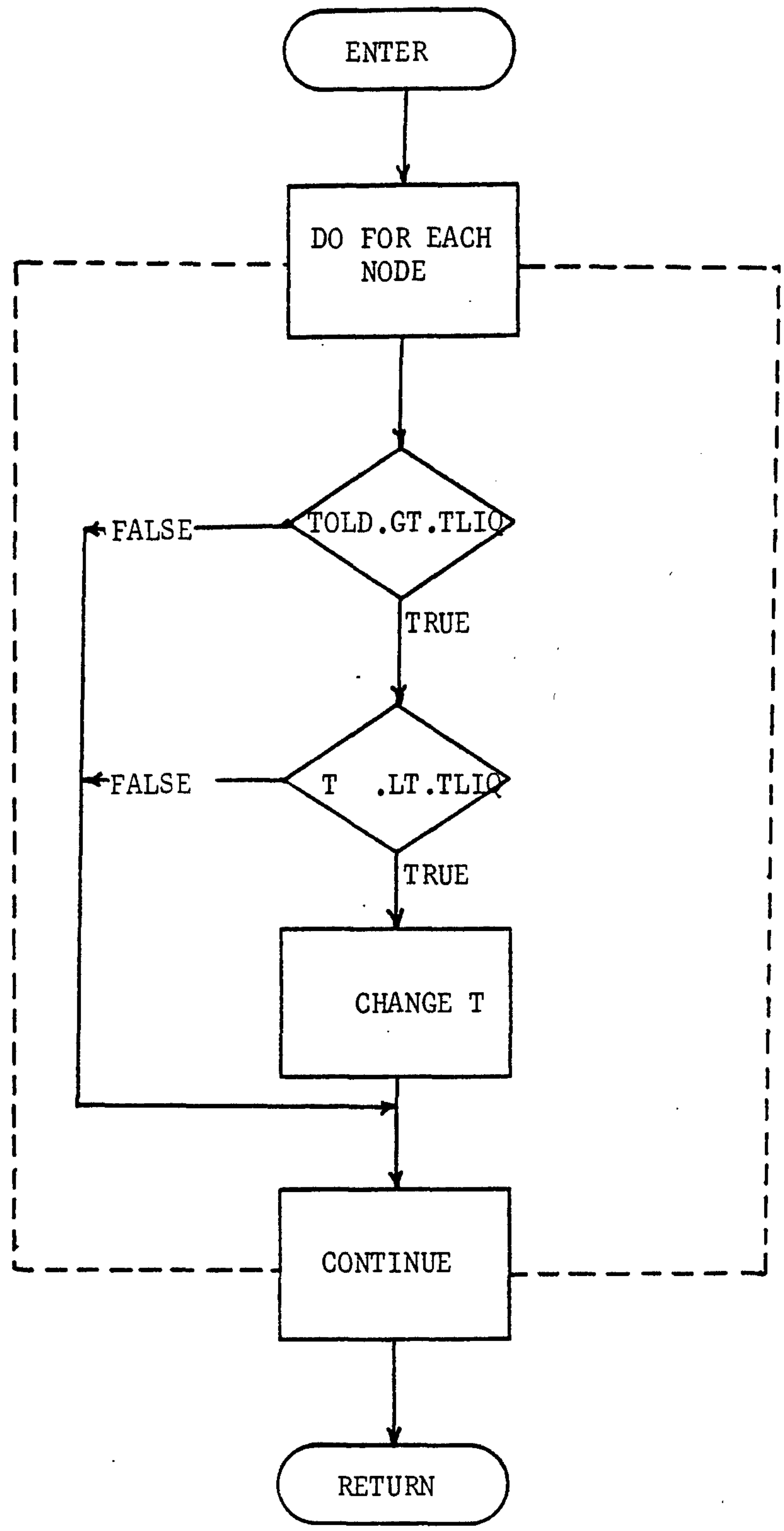

Figure E2-3-5: Temperature adjustment flow chart.

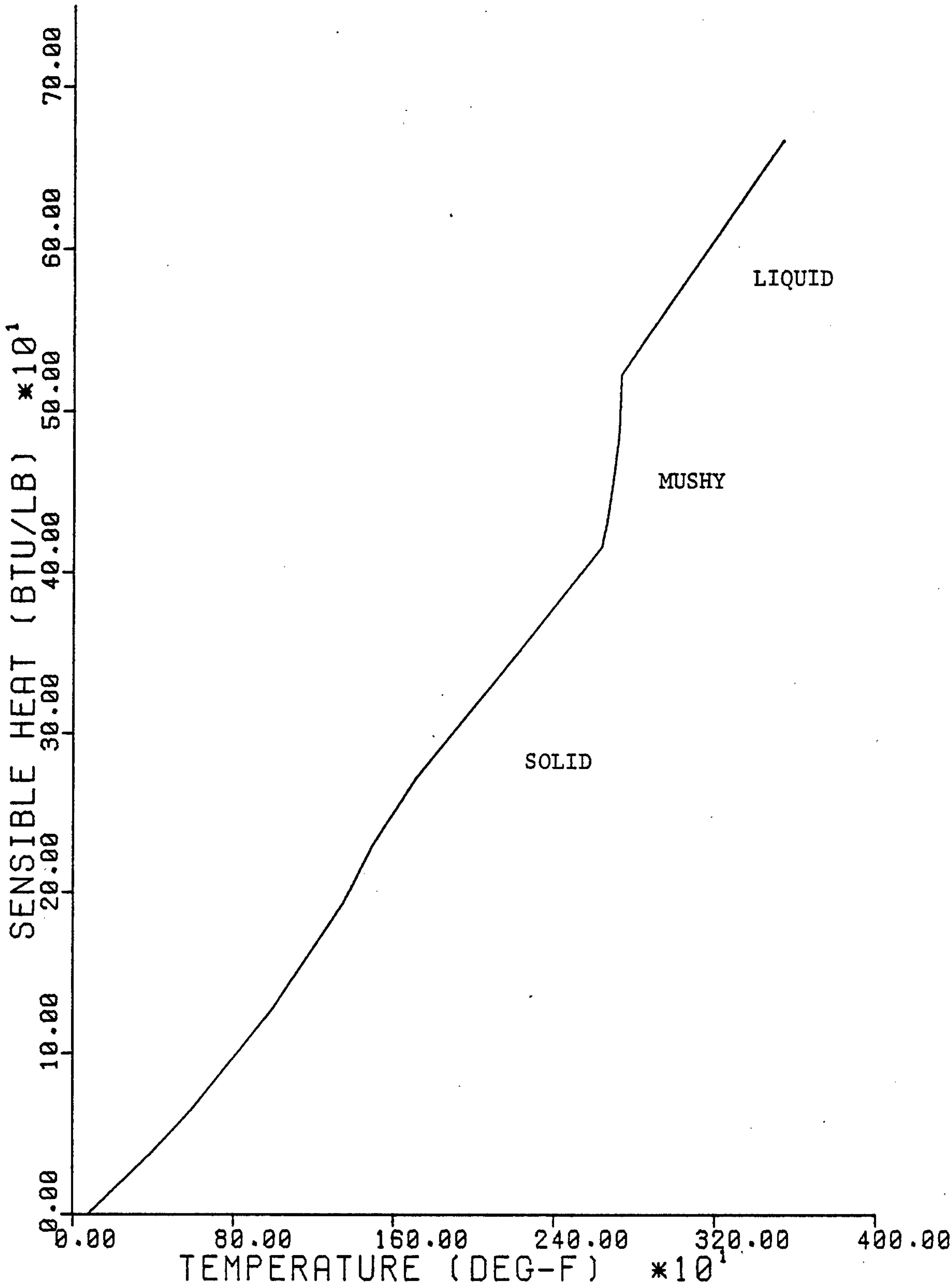

Figure E2-3-6: Adjustment's basis on enthalpy

$$\Delta E = (TOLD - TLIQ)\ CPL + (TLIQ - TADJ)\ CPM \qquad (3\text{-}19)$$

where TLIQ is the liquidus temperature, TADJ, is the corrected final temperature and CPM is the heat capacitance, in the mushy zone. Solving these two equations for the adjusted temperature TADJ we get

$$TADJ = TLIQ - \frac{(TLIQ - TNEW)\ CPL}{CPM} \qquad (3\text{-}20)$$

For the values TOLD = 2800^{o}F, TNEW = 2680^{o}F, TLIQ = 2735^{o}F, CPL =0.18 BTU/LB F, the adjusted temperature TADJ is calculated to be 2726^{o}F. The corrected temperature is 46^{o}F higher than the unadjusted temperature. The presence of solidification receives special treatment in CSSP.

E2-3-5 Material Properties

In all modeling, it is important to have accurate values of material properties. Some properties will influence the simulation more than others. Paschkis (2) studied the influence of varying casting thermal properties, thus demonstrating the importance of having accurate material properties.

The properties of the sand and the temperature-dependent properties of the steel, initially used in this project, were derived from a consensus of the properties in the published literature. The sand properties are constant, but the steel has a different set of properties for the solid, mushy, and liquid zones. In order to conserve computer time and because trial runs showed the analysis of freezing behavior was not strongly affected, constant values of the thermal properties were selected within each range. These values are shown in Table E2-3-1. Note how the capacitance of the mushy zone has been artificially increased to account for the heat of fusion that is released during freezing.

Essentially, two types of heat transfer are present in the problem.

a. Conduction. Condustion in the metal, in the sand, and between the metal and sand is modeled.

b. Convection. Convection from the exposed surfaces of the sand mold to the atmosphere is simulated.

These two heat transfer mechanisms are coupled with a method to handle the latent heat of fusion to give an accurate simulation of solidification. Convection within the liquid has not been included. However, its effect on temperature distribution within the liquid may be approximated readily by using an enhanced thermal conductivity (3).

E2-3-6 Assumptions to Simplify Analysis

The solidification of castings is a coupled thermal and metallurgical system involving a phase change. Thus, to develop an economical simulation, assumptions are made that simplify the analysis. The assumptions in this problem are:

Table E2-3-1

Material Properties Used in CSSP

Material	Conductivity BTU/(ft hr deg F)	Density lb/ft3	Heat Capacitance BTU/(lb deg F)
Sand	0.2	99.0	0.21
Steel Solid	18.0	489.0	0.18
Mushy	15.0	489.0	1.57
Liquid	10.0	489.0	0.21

1. Artificial heat capacitance.

2. Constant thermal properties within each phse region.

3. No thermal resistance at alloy/sand interface.

4. Casting instantaneously filled.

5. Mold temperature initially uniform.

The first assumption means that an artifically rasied heat capacitance in the mushy zone adequeately represents the latent heat of fusion as described in paragraph E2-3-4. The use of constant thermal properties is discussed in paragraph E2-3-5.

The sand-metal interface is an area where heat flow may be impeded. For example, during solidification, the casting may shrink because the density of the solid phase is greater than the density of the liquid phase. Hence, an air gap may for betwwen the sand and the metal. The air gap decreases the contact at the interface and increases the resistance to heat flow. Likewise, it is possible for chemical reactons to take place at the interface. These chemical reactons may produce oxide layers that would increase the resistance to heat flow across the interface. The simulation procedure ignores any resistance to heat flow at the interface and considers the contact between the sand and the metal to be intimate. This assumption is reasonable because the sand is a very poor conductor. The inclusion of interface resistance between the sand and the metal would not be significant in comparison to resistance to heat flow in the sand mold.

The speed of pouring liquid metal into the mold can influence the initial temperature of the metal. Slow pouring yields a nonuniform temperature distribution. The first section poured has cooled some by the time the last seciton has been poured. The last section poured has a higher temperatuer then the first section poured. Infinitely fast pouring would yield a uniform temperature distribution. The simulation neglects the possible variation of pouring speed and assumes perfect pouring methods are used.

Concommitantly, there is some heat flow from the molten alloy to the sand while the mold is being filled. The inclusion of this phenomenon would complicate the simulation procedure. Hence, the mold is assumed to be already filled with liquid metal, and any heat flow during the filling of the mold is neglected. These assumptions, then, simplify the analysis without significantly detracting from its accuracy. Simple methods, however, are available for approximating the influcne of pouring time on initial temperatures. These effects may be tested.

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E2-4 INPUT FORMAT CSSP AND AGRID

E2-4-1 Required Input Data

The initial steps in the use of CSSP are to (a) describe the geometry of the casting cavity and the mold (flask or corebox) in a form readable by the computer program, (b) subdivide the sand regions and casting cavity regions into nodes and elements, (c) input the goemetry to the computer, (d) input the node and element goemetric informaton, (e) assign material properties to the elements and initial temperatures to the nodes, (f) select an initial time increment for the calculation and the total time to be simulated. These steps may be prepared totally by hand and then entered into the computer or they may be prepared in general form on paper and then calculated in detail and put in the form of an input file for CSSP using a mesh generation program such as BCAST (described in Exhibit 1), UNISTRUC (software developed by Control Data Corporation), or AGRID (described in later sections of this chapter). Interfaces between BCAST or UNISTRUC and CSSP have not yet been developed and tested. AGRID has limited utility.

The input file to CSSP should include the following information:

(1) The time increment, Δt: The program computes the temperature at each node within the sand and alloy at a given time, t, and then repeats the computation at a later time, $t + \Delta t$. One method of determining Δt is given in paragraph E244.

(2) The number of iterations: The product of the number of iterations and the time increment determines the time to be simulated.

(3) The node numbers: Each node is designated by a number. The selection of node numbers influences the amount of computer time and stoarage needed through the bandwidth.

(4) The global coordinates of the nodes: An X,Y,Z cartesian coordinate system should be used to describe the positions of the nodes selected for the finite element analysis.

(5) The element numbers: Each element is designated by a number.

(6) The element shape: In CSSP the input elements may be (see figure E2-3-1).

tetrahedrons - 4 nodes

wedges - 6 nodes

hexahedrons - 8 nodes

(7) The numbers of the nodes that make each element: Nodes may be shared by several elements.

(8) The material type codes for each element: Presently, CSSP will handle elements of sand (code = 2) and alloy (code = 1). Other materials will be added in Phase II.

(9) Interface codes for each element: The method of heat transfer from each face of an element must be described by a two digit code. For example, 00 indicates conduction to a neighboring element. Other codes are listed later.

(10) Initial temperatures of the nodes: An initial temperature must be specified for each node. Generally, nodes in sand regions will be room temperature e.g., 80^{o}F; nodes in alloy regions will be slightly above the liquidus, e.g., 2,800^{o}F; and nodes at the mold/alloy interface will be at an intermediate temperature, e.g., 2,650^{o}F.

(11) Specified temperatures of selected nodes: If a constant temperature boundary condition is desired, the numbers of the fixed temperature nodes and the specified temperatures must be given.

(12) Bandwidth: The bandwidth depends on the largest difference in node number within an element.

It is clear that if 3,000-10,000 nodes and elements are desired for analysis, a very large data file must be prepared.

E2-4-2 Input Format For CSSP

CSSP will handle input data in the following format:

line 1	time step; number of iterations
line 2	maximum difference in node numbers within an element
line 3	total number of nodes (N)
next N lines	node number; X,Y,Z coordinates
line N + 4	number of specified temperatures
line N + 5	number of tetrahedral elements (assumed for this example to be 0)
line N + 6	number of hexahedral elements (assumed to be H)
next H lines	element number plus numbers of the 8 nodes defining each element
next H lines	material type for each element and interface code for each of 6 faces of hexahedron

line N + 2H + 7 number of wedge elements (assumed to be 0)

next N lines initial temperature of each node.

The groups of data were discussed briefly above. Nevertheless, a more specific discussion of element definitions, material codes, and interface codes would be enlightening. The hexahedrons will be used as an ecample. The first line in the element definition area (line N7) would be of the form

1	11	9	1	3	12	10	2	4
Element Number	The numbers of the eight nodes that define the element							

Thus, each line in this area defines an element.

E2-4-3 AGRID

A routine, AGRID, has been prepared to help generate a finite element mesh description. AGRID will accept geometric description of the casting in terms of brick shapes - up to five. In preparation for using AGRID the casting and flask should be sketeched and a set of X, Y, Z coordinates assigned to the corner of each brick shape. AGRID will help generate only hexahedral (brick) elements. Again the desired node and element distribution should be sketched prior to using AGRID. The elements are formed by passing X, Y, Z planes through the zones. The coordinate where each plane cuts the coordinate axis should be recorded. AGRID is diminsioned to accept up to 3,000 nodes. AGRID will number the nodes and elements, compute the X, Y, Z coordinates of all nodes, and prepare a file in proper format for input to CSSP.

AGRID is used interactively on a timesharing, teletype terminal. On the PITT DEC 10 computer system B the user initieates use of AGRID by typing

```
EXecute AGRID.FOR
```

The program will ask questions in the proper order for preparation of the data file. When the data arrangement is completed by AGRID it will be in two files.

```
FIRST.DAT

SECOND.DAT
```

These files should be combined into a single file with its own name by typing

```
RENAME XXXXXX.DAT = FIRST.DAT, SECOND.DAT
```

If the input file will not be used immediately, it should be placed on tape by typing the following

```
DRIVES MT9

MOUNT MT9:  UARC/WE/VID:  B14730/SL

R UARC

FREEZE XXXXXX.DAT

CONTROL C
```

An example is given in the next chapter.

E2-4-4 Selecting a Timestep

The selection of the time increment influences the ability to obtain convergence, stability, in the finite element solution. The following calculation is suggested

$$\Delta t = \Delta X^2/4\alpha$$

where ΔX is the node spacing in the region if highest expected temperature gradient, usually the sand near the mold metal interface and α is the thermal diffusivity, i.e., thermal conductivity divided by density times heat capacity. (See Table E2-3-1 for thermal properties of armor steel and no bake sand).

E2-5 EXAMPLE PROBLEM PROCEDURE: CSSP AND AGRID

The finite element method can be more easily understood by looking at an example problem. This example will contain the general approach to solving a heat transfer problem. Suppose there is a metal block inside a sand mold as pictured in Figure E2-5-1. The problem is to find the resulting transient temperature behavior if the metal is initially at 2850°F, the sand at 100°F, and the interface between the two materials is at 2650°F. The first step towards the solution is to prepare the input file for CSSP. For a simple geometry like this one, a mesh can be drawn by hand (Figure E2-5-2) and then the input file can be created interactively by executing AGRID.FOR.

The creation o an input file for this problem was performed interactively on a teletype terminal linked by telephone line to the PITT DEC 10 computer system B. The session record is shown in Figure E2-5-3. A "." is a prompt from the system B monitor indicating it is ready to receive a monitor command. The first command given was to load, compile, and execute AGRID.FOR. Lines not preceded by a prompt singnal were typed by the computer at the direction of the system monitor or AGRID. A line preceded by ">" was typed by the user. Thus, the ">" is a prompt from the program that indicates the computer program is wainting for a response from the user. This means of data preparation requires the user to be knowledgable in designing finite element meshes. A completely automatic mesh generation program, BCAST, is being developed, presently. (Refer to Exhibit 1).

Now, looking at the data input file, one sees the result of the interactive session. The notations inside the brackets are descriptions of the data and are not part of the data input file. (See Figure E2-5-4).

The simulation may run on the timesharing system (for problems with 100 nodes or less) or by creating a batch control file using the timesharing system. The batch control file mounts the proper tape, loads the program, CSSP, and the input file, XXXXXX.DAT, executes the simulation, and places the output data file, YYYYYY.DAT, executes the simulation, and places the output data file, YYYYYY.DAT, on tape ready for post processing. An example of a batch control file created on a teletype linked to the PITT SEC 10 system B is shown in Figure E2-5-5.

To be of any use the putput must be postprocessed. There are several options on what to do with the data.

1. Temperature profile maps
2. Plot temperature vs. time
3. Plot temperature vs. position
4. Plot vs. time cooling rate
5. Plot temperature gradient vs. position

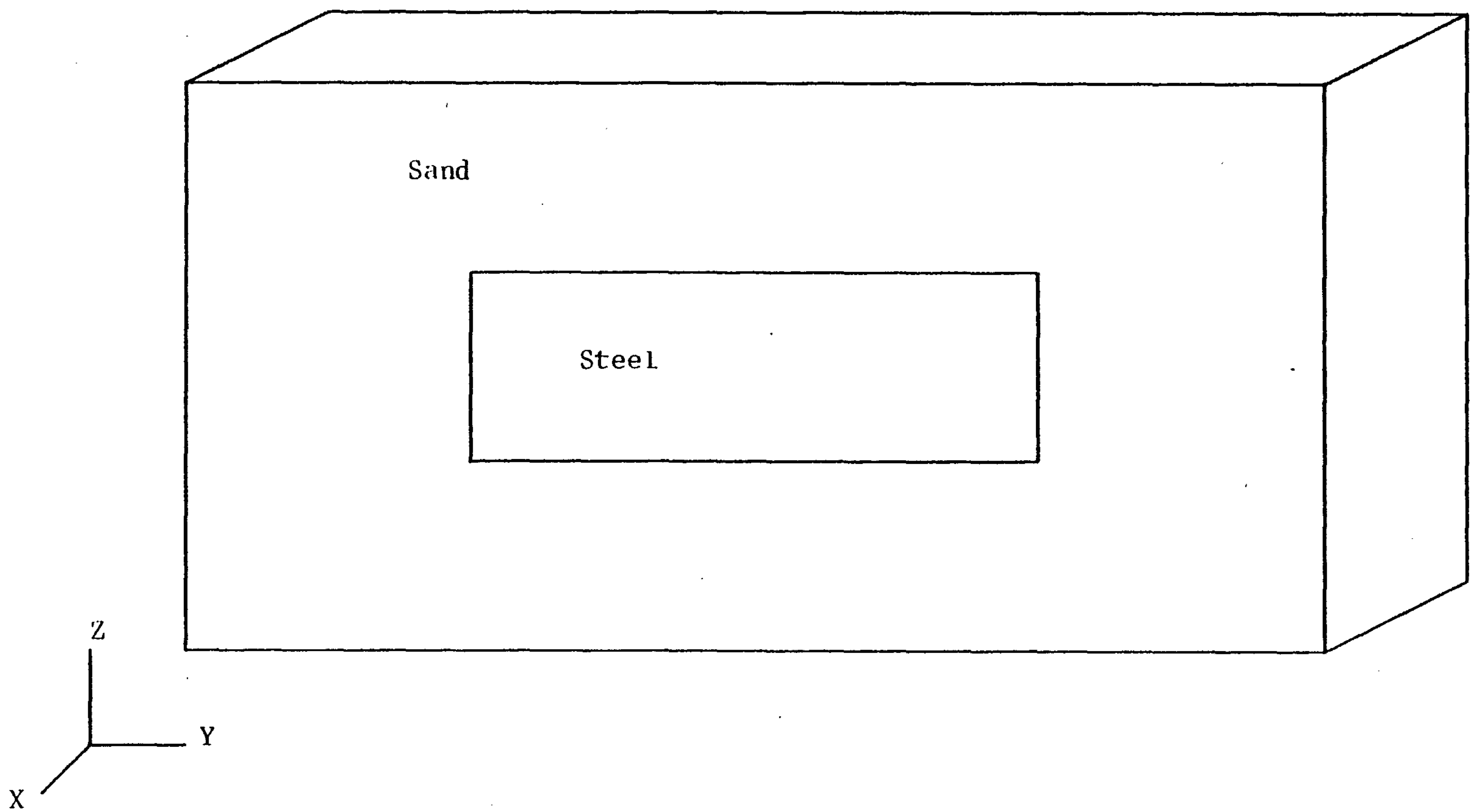


Figure E2-5-1: Example problem sketch.

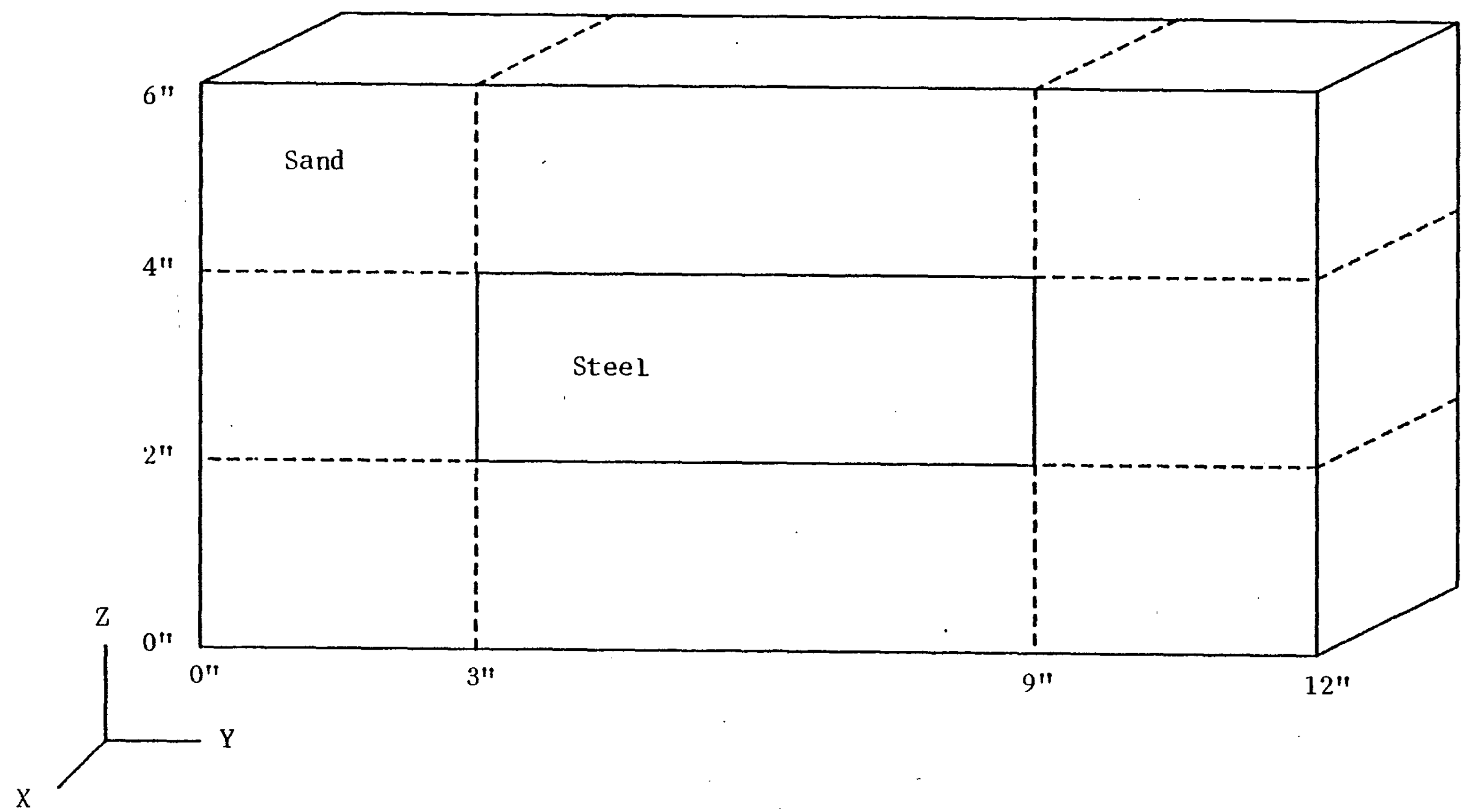


Figure E2-5-2: Hand drawn mesh for example problem.

```
.EXECUTE AGRID.FOR
LINK:   Loading
[LNKXCT AGRID execution]

THIS IS AN INTERACTIVE PROGRAM TO CREATE
THE INPUT FILE FOR A CSSP HEAT TRANSFER SIMULATION
THE CREATED MESH WILL CONTAIN ONLY BRICK ELEMENTS
WHAT IS THE SIZE OF THE TIMESTEPS (HRS)
>0.5
HOW MANY ITERATIONS TO BE SIMULATED?
>20
WHAT ARE THE TEMPERATURES IN THE PROBLEM?
USING DEG-F ENTER INITIAL TEMPERATURES FOR
POURING     INTERFACE    AND MOLD ON THE SAME LINE
>2850.        2650.           100.
HOW MANY PLANES IN THE Z DIRECTION?
>4
HOW MANY PLANES IN THE Y DIRECTION?
>4
HOW MANY PLANES IN THE X DIRECTION?
>2
TYPE IN THE Z-PLANE VALUES USING ONE LINE FOR EACH (IN)
>0.
>2.
>4.
>6.
TYPE IN THE Y-PLANE VALUES (IN)
>0.
>3.
>9.
>12.
TYPE IN THE X-PLANE VALUES (IN)
>0.
>1.
THE CASTING MUST BE DIVIDED INTO FIVE OR FEWER PARTS
TYPE IN THE NUMBER OF BRICK PIECES
>1
```

Figure E2-5-3: Interactive session with AGRID for sample problem.

```
TYPE IN THE COORDINATE LIMITS FOR EACH PIECE (IN)
FIRST LOW VALUE AND THEN HIGH VALUE ON SAME LINE
THIS IS FOR PIECE NUMBER      1
X-LOW      X-HIGH
>0.      1.
Y-LOW      Y-HIGH
>3.      9.
Z-LOW      Z-HIGH
>2.      4.
 THE COMPLETE MESH IS NOW GENERATED
NOW TYPE
.R PIP
*XXXXX.DAT=FIRST.DAT,SECON.DAT
PRESS CONTROL C
THE FINAL INPUT FILE IS NOW CALLED XXXXX.DAT
STOP

End of execution    FOROTS 5B(1001)
CPU time: 0.56  Elapsed time: 1:28.12
EXIT

.R PIP

*INPUT.DAT=FIRST.DAT,SECON.DAT
```

Figure E2-5-3: (Continued).

```
.05000    20
  11                                          [Timestep  Number]
  32                                          [Node Difference]
   1   0.0000    0.0000    0.0000                  [Nodes]
   2   1.0000    0.0000    0.0000
   3   0.0000    0.0000    2.0000
   4   1.0000    0.0000    2.0000
   5   0.0000    0.0000    4.0000
   6   1.0000    0.0000    4.0000
   7   0.0000    0.0000    6.0000
   8   1.0000    0.0000    6.0000
   9   0.0000    3.0000    0.0000
  10   1.0000    3.0000    0.0000
  11   0.0000    3.0000    2.0000
  12   1.0000    3.0000    2.0000
  13   0.0000    3.0000    4.0000              [Node      x    y    z]
  14   1.0000    3.0000    4.0000              [No.       Coord.      ]
  15   0.0000    3.0000    6.0000
  16   1.0000    3.0000    6.0000
  17   0.0000    9.0000    0.0000
  18   1.0000    9.0000    0.0000
  19   0.0000    9.0000    2.0000
  20   1.0000    9.0000    2.0000
  21   0.0000    9.0000    4.0000
  22   1.0000    9.0000    4.0000
  23   0.0000    9.0000    6.0000
  24   1.0000    9.0000    6.0000
  25   0.0000   12.0000    0.0000
  26   1.0000   12.0000    0.0000
  27   0.0000   12.0000    2.0000
  28   1.0000   12.0000    2.0000
  29   0.0000   12.0000    4.0000
  30   1.0000   12.0000    4.0000
  31   0.0000   12.0000    6.0000
  32   1.0000   12.0000    6.0000       [No. of Specified Temp.]
   0                                          [Tetrahedrons]
   0                                          [Hexahedrons]
   9
```

Figure E2-5-4: Input file to CSSP created by AGRID.

[Element Definitions]

1	11	9	1	3	12	10	2	4
2	13	11	3	5	14	12	4	6
3	15	13	5	7	16	14	6	8
4	19	17	9	11	20	18	10	12
5	21	19	11	13	22	20	12	14
6	23	21	13	15	24	22	14	16
7	27	25	17	19	28	26	18	20
8	29	27	19	21	30	28	20	22
9	31	29	21	23	32	30	22	24

[Material and Interface Codes]

1	2110000	1512
2	2110000	12
3	2110000	140012
4	2110000	1500
5	1110000	0
6	2110000	140000
7	2110013	1500
8	2110013	0
9	2110013	140000
0		

[Wedges]

[Node No. Initial Temperature]

Node No.	Initial Temperature	Node No.	Initial Temperature
1	100.0000	21	2650.0000
2	100.0000	22	2650.0000
3	100.0000	23	100.0000
4	100.0000	24	100.0000
5	100.0000	25	100.0000
6	100.0000	26	100.0000
7	100.0000	27	100.0000
8	100.0000	28	100.0000
9	100.0000	29	100.0000
10	100.0000	30	100.0000
11	2650.0000	31	100.0000
12	2650.0000	32	100.0000
13	2650.0000		
14	2650.0000		
15	100.0000		
16	100.0000		
17	100.0000		
18	100.0000		
19	2650.0000		
20	2650.0000		

Figure E2-5-4: (Continued).

```
$JOB TCF [*, *]/CORE:125K/TIME:0:58:0/OUTPUT:0/PRIOR:2
$DRIVES MT9
.MOUNT MT9:UARC/WE/VID:B14730/SL
.R UARC
*THAW MESH.DAT,CSSP.FOR
%FIN:
. R PIP
*MESH2.DAT=MESH.DAT
%FIN:
.EXECUTE CSSP.FOR
.COPY TEMP.DAT=STEMP.DAT
.R UARC
*FREEZE TEMP.DAT
%FIN:
.DISMOUNT MT9
.UNDRIVES
.DELETE TEMP.DAT,MESH2.DAT,STEMP.DAT,CSSP.*,MESH.DAT
$DATA
$EOD
$EOJ
```

Figure E2-5-5: Batch control file for CSSP.

Routines for postprocessing the data are illustrated in the next chapter.

The information in this file is the required input for CSSP. The size of the timestep used to simulate transient behavior and the total number of timesteps are input. The total simulated time is equal to the number of timesteps multiplied by the size of each timestep. The greatest difference that occurs between the numbering of the nodes in any element is input to help reduce computation time in the equation solving routine. This node difference is found by searching the elements and their nodes. It will help to reduce computation by defining the maximum number of nonzero coefficients in each equation. The equation solving routine uses only the nonzero coefficients. The procedure of subdividing the geometry of the problem involves creating nodes. The input needs the number of nodes and the X,Y,Z coordinates of each node. Sometimes, one may wish to keep the temperature of a node constant during simulation. Hence, one must input the node numbers and their corresponding specified temperature. CSSP is capable of handling tetrahedrons, hexahedrons, and wedges. The number of elements present and the nodes which define a particular element are part of the input. Every element is composed of a type of material. The type of material is obtained by looking at the element's material code, a single digit whose value corresponds to a specific material. Also, for each element, the boundary conditions are specified by a series of double digit numbers. Additionally, the initial temperature of each node must be input.

E2-6 POSTPROCESSING ROUTINES: S, TEMPOS, RATES, GRAD, MAP

The data output from the simulation of heat flow on a complex casting (e.g., 3,000 nodes and 20 time increments) will be voluminous. This data may be obrained for detailed analysis by requesting a printout. However, routines have been developed to allow graphical analysis of the simulation output highlighting the data of interest to casting engineers. The routines developed to date include:

GRAD.FOR	Plots temperature gradient, the first derivative of temperature with position at selected times
MAP.FOR	Plots freezing profile maps illustrating the progress of solidification
S.FOR	Plots cooling curves, temperature versus time for selected positions (nodes)
RATES. FOR	Plots cooling rates, the first derivative of temperature with time at selected positions
TEMPOS. FOR	Plots temperature distributions, temperature versus position at selected times.

In general, the output of a heat flow simulation by CSSP will form a file stored on tape and given a name with the extension DAT, e.g., YYYYYY.DAT. This can be obtained for printout by mounting the tape, thawing the file, and requesting a printout

PRINT YYYYYY.DAT

The use of the plot routines is illustrated by application of CSSP to a stepped plate casting similar to the test castings used in the experimental phase of the development of the CAD/CAM CASTING PROCESS. In the simulation of the test plate a slice along the centerline was considered. In the sand and casting about 2,900 nodes and elements were used. The initial armor steel temperature was taken as 2,800°F, the interface temperature as 2,650°F, the sand temperature as 80°F. Using the relation presented earlier

$$\Delta t \geq \frac{\Delta X^2}{4\alpha} \tag{6-1}$$

a timestep of 3 minutes was slected.

E2-6-1 Geometry

The general geometry of the problem is three-dimensional with a sand mold surrounding a steel casting. The simulation program is desinged to simulate any shape. The shape of test casting used as an illustra-

tive example is platelike and is shown in Figure E2-6-1. (It is similar to test plate casting A of the experimental program). The simulated configuration has four steps; these include: (a) 7-x 6-x 3-in., (b) 7-x 9-x 2-in., (c) 7-x 6-x1 1/2-in., and (d) 7-x 5-x 1-in., plates, attached to a cylindrical riser 9 1/2 in., high and 6-in., diameter. The riser acts as a reservoir of liquid metal. The sand surrounding the casting is contained in a 14-x 40-x 10-in over 7-in., rectangular flask. The parting line is at the top of the plate. A centerline view of the casting as prepared by AGRID is shown in Figure E2-6-2. The positions of selected nodes are shown in Figure E2-6-3.

E2-6-2 Freezing Profile Mapes: MAP

The directionality (progressivness) of the freezing pattern can be seen by examining Figures E2-6-4 through E2-6-8 produced by MAP. FOR. Each of the figures is a centerline view of the casting and the sand mold. The casting and riser are outlined by solid lines (slightly displaced from actual positions). Each node is represented by a temperature symbol:

- ">" means the temperature is less than 2643°F and for armor steel indicates solid
- "-" means the temperature is between 2643°F and 2735°F (the solidus and the liquidus temperatures for armor steel) and for armor steel indicates the mushy zone, solid plus liquid
- " " a blank means the temperature is above 2,735°F and for armor steel indicates liquid.

The casting solidifies from right to left with the riser area solidifying last. This is the directional solidification that the casting was designed to produce so that the riser could feed liquid metal to other sections thereby reducing any possible shrinkages occuring in solidification. Next, by looking at the corners of the riser, one can see faster cooling at corners surrounded by sand and slower cooling at corners where the riser and casting meet. This is what basic heat transfer principles would suggest. Additionally, these figures imply that freezing time almost 12 minutes.

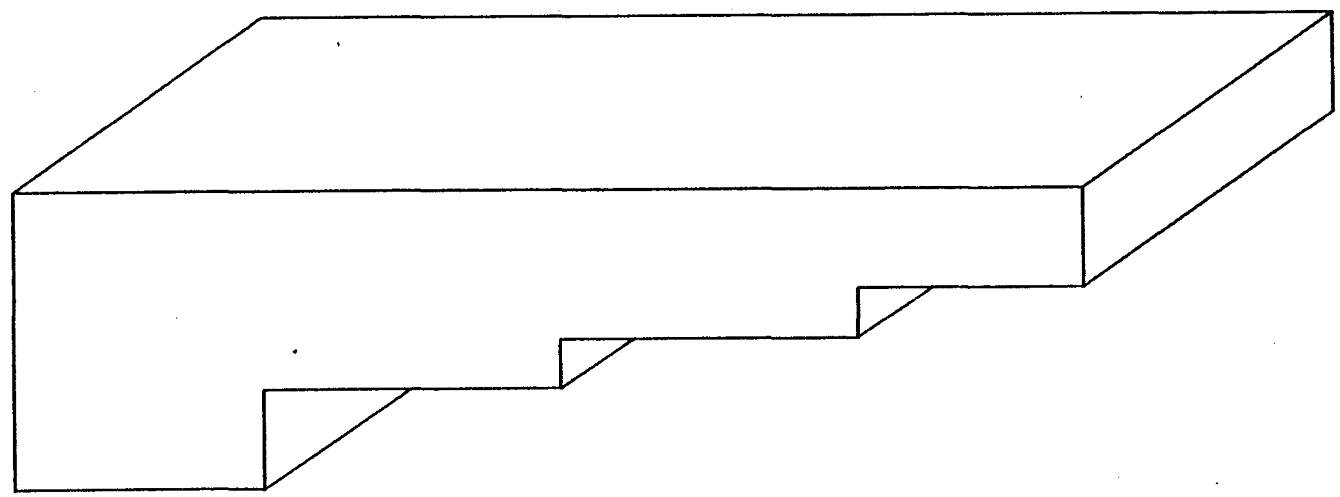


Figure E2-6-1: Test plate casting.

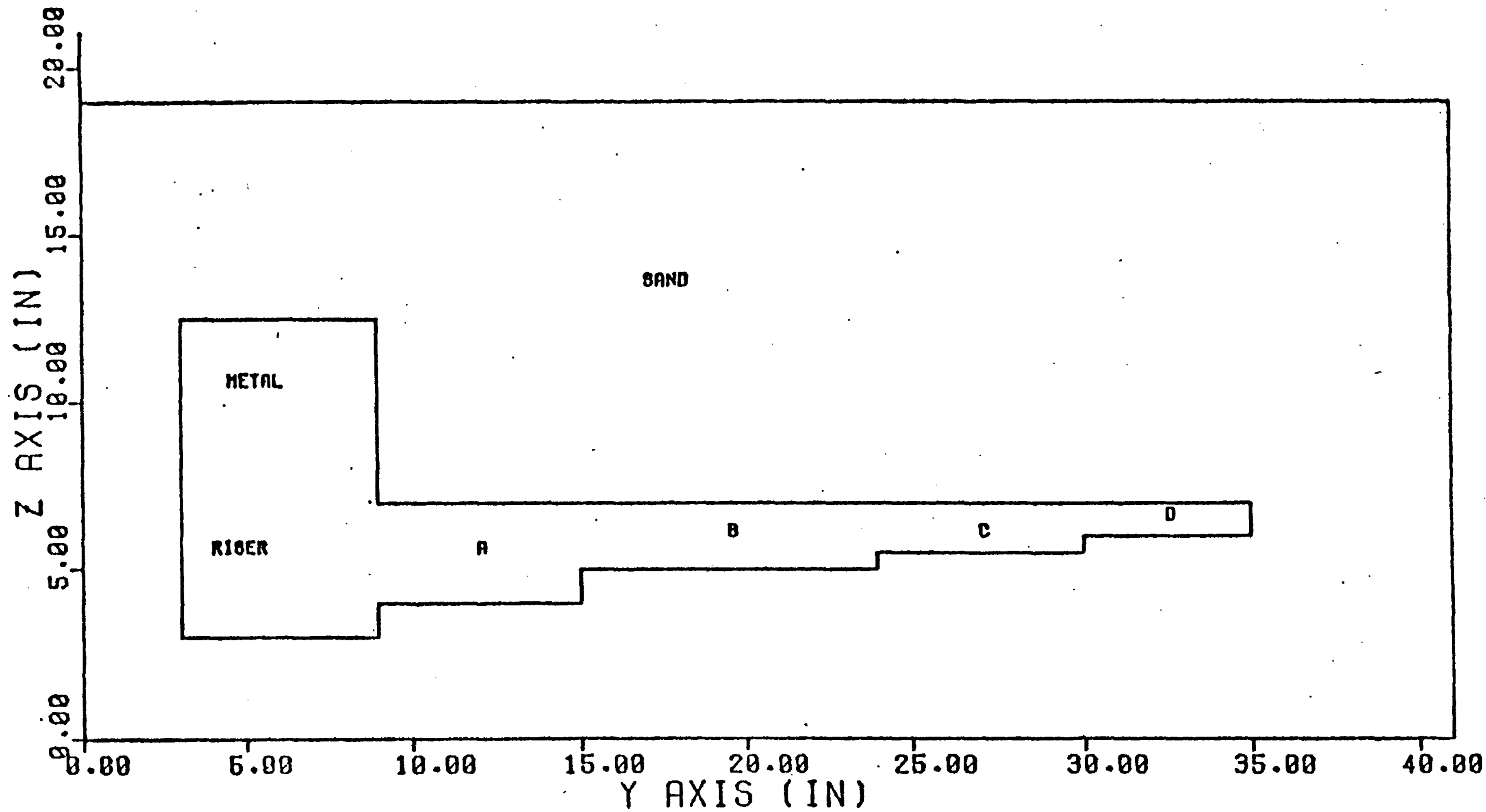


Figure E2-6-2: Centerline view of casting configuration.

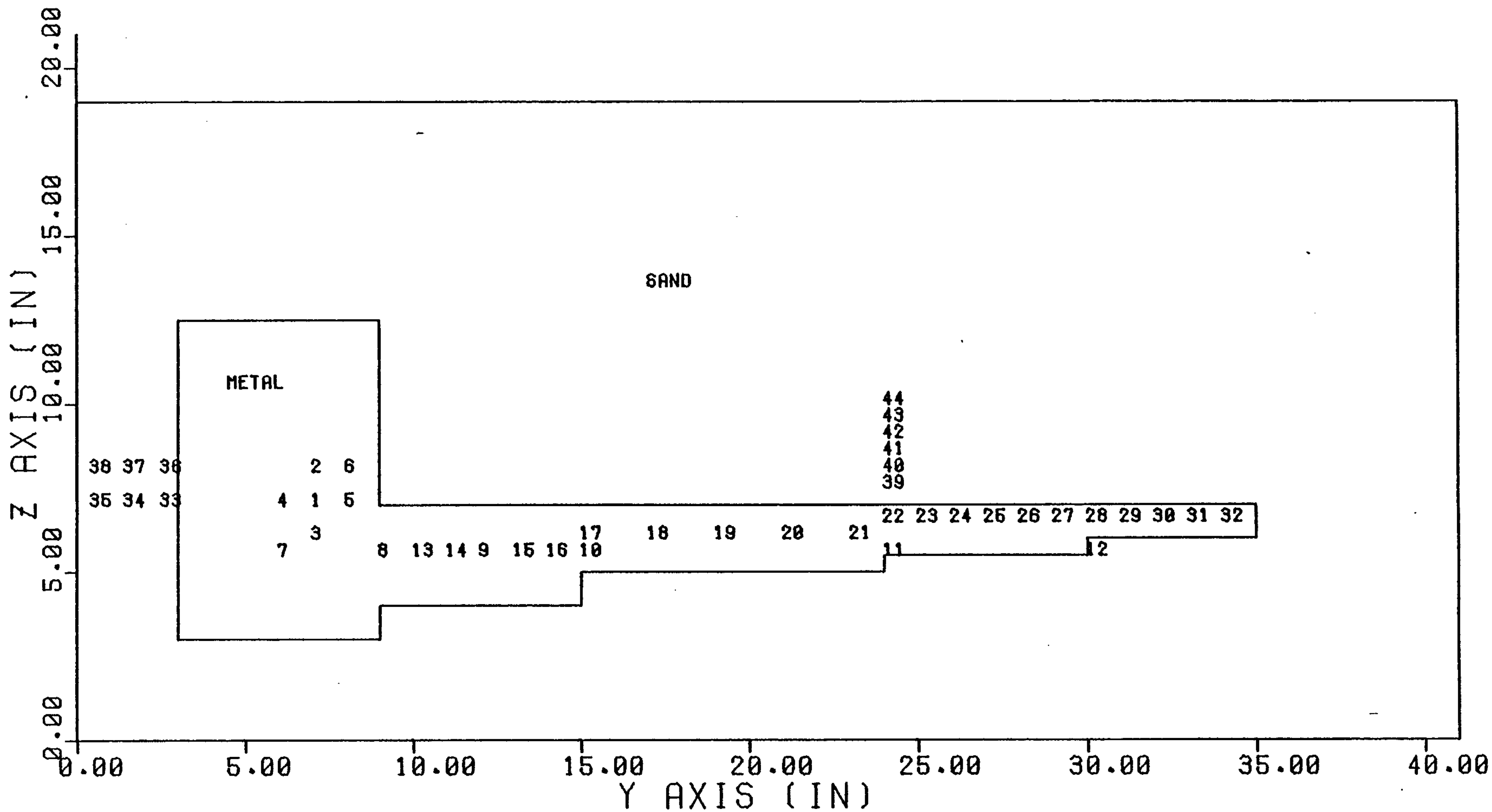
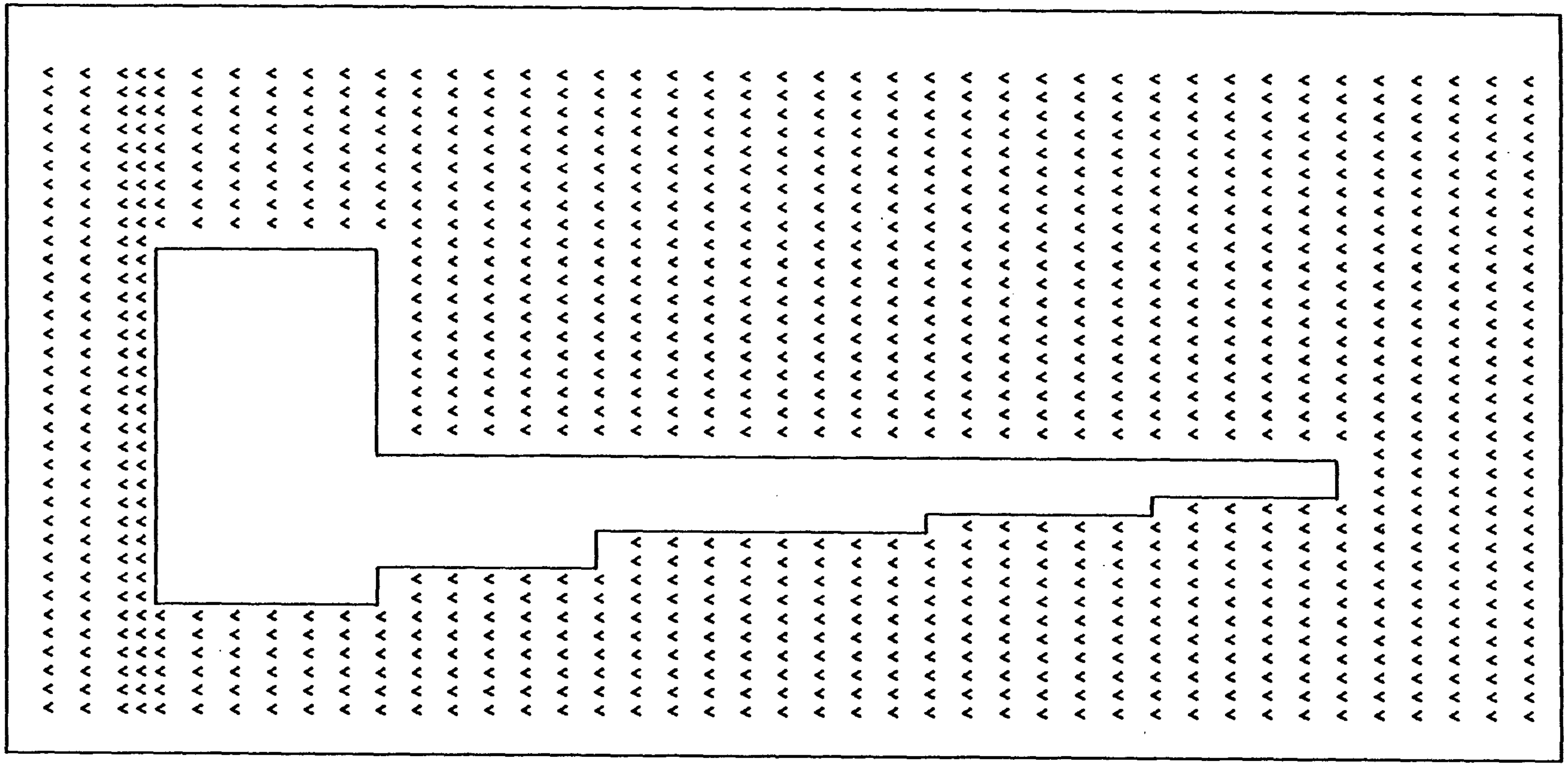
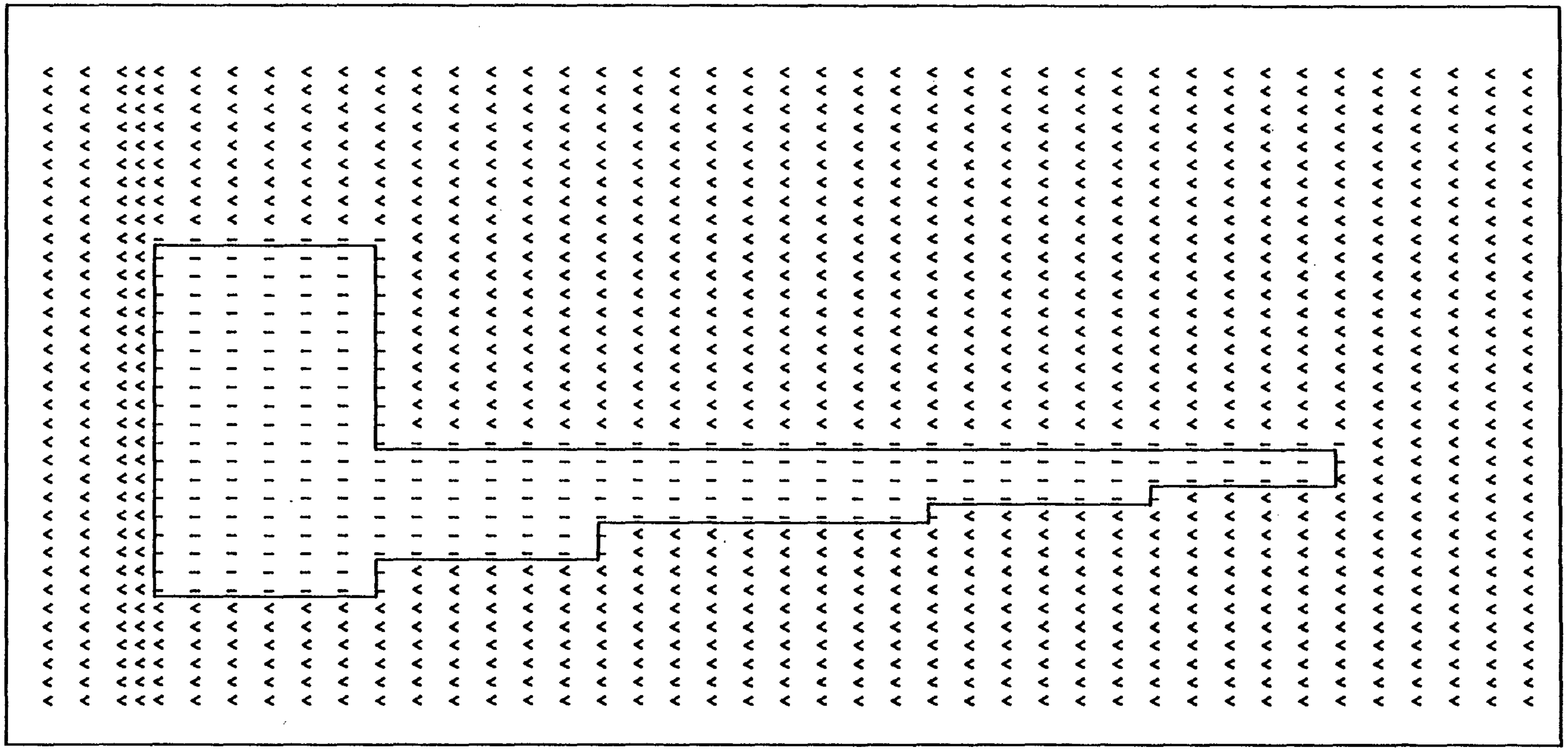


Figure E2-6-3: Locations of points plotted in simulation cooling curves.



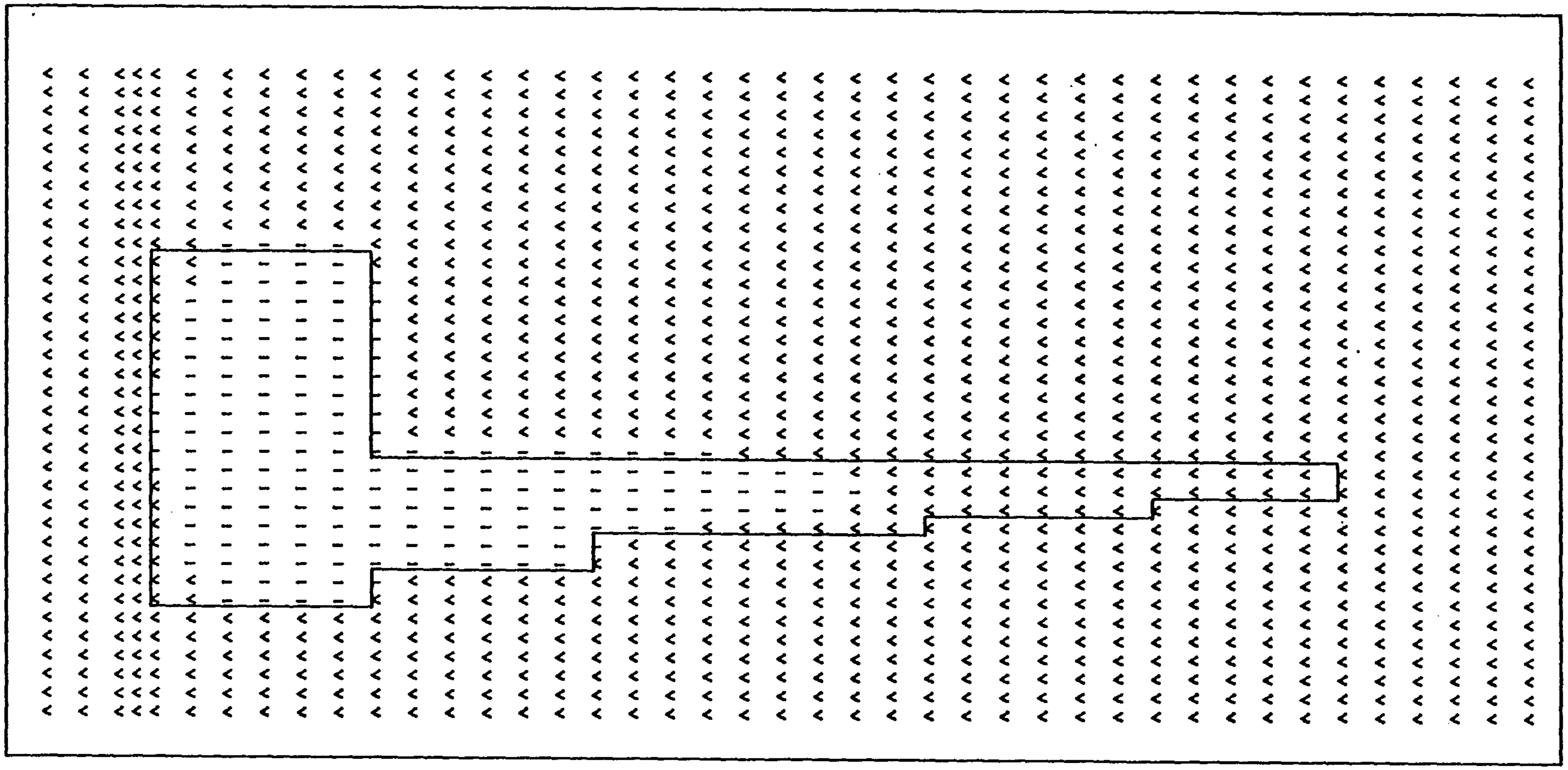
TIME (MIN) = 0.00

Figure E2-6-4: Simulated freezing progression map for stepped plate castings, time = 0 min.



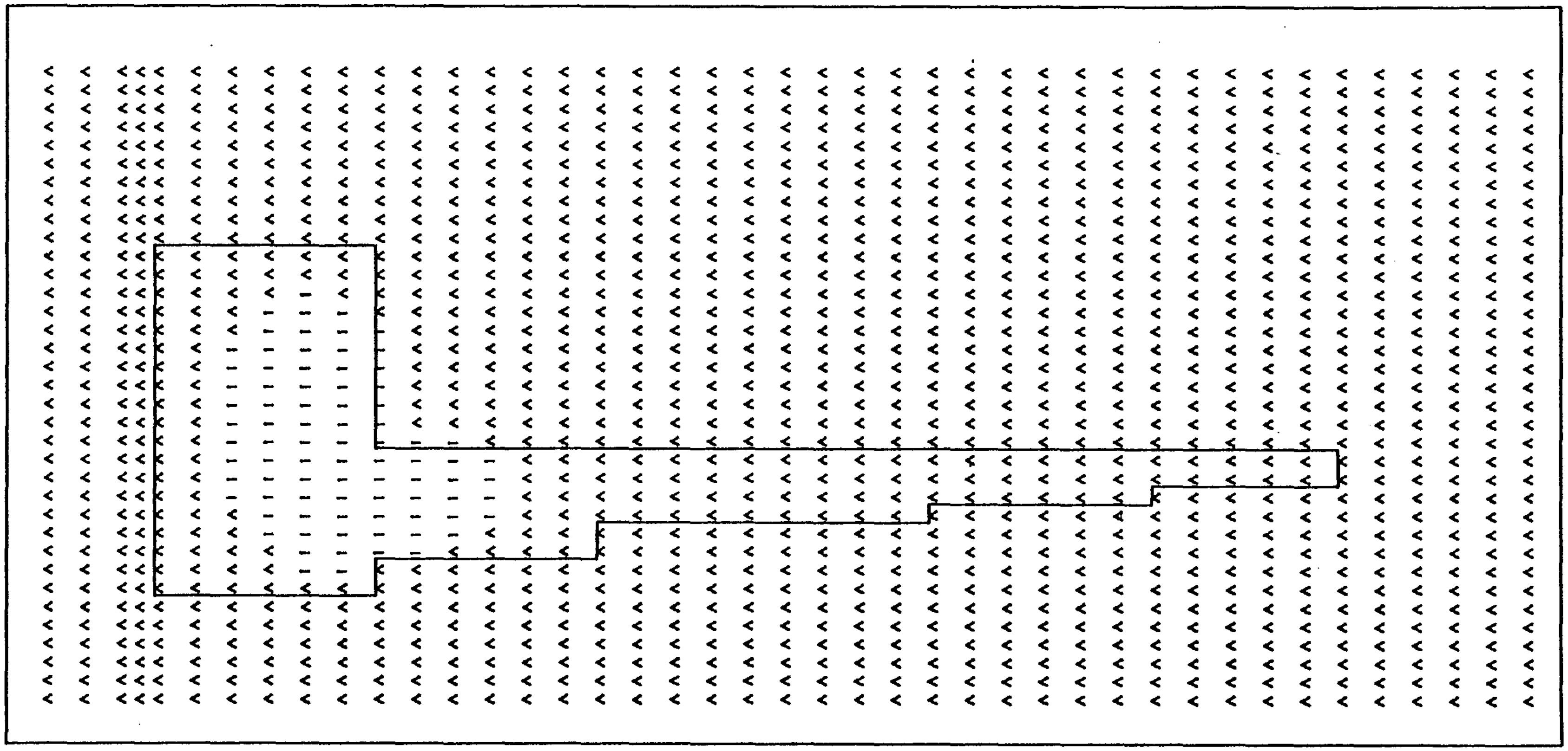
TIME (MIN) = 3.00

Figure E2-6-5: Simulation temperature map for test casting centerline at time = 3 min.



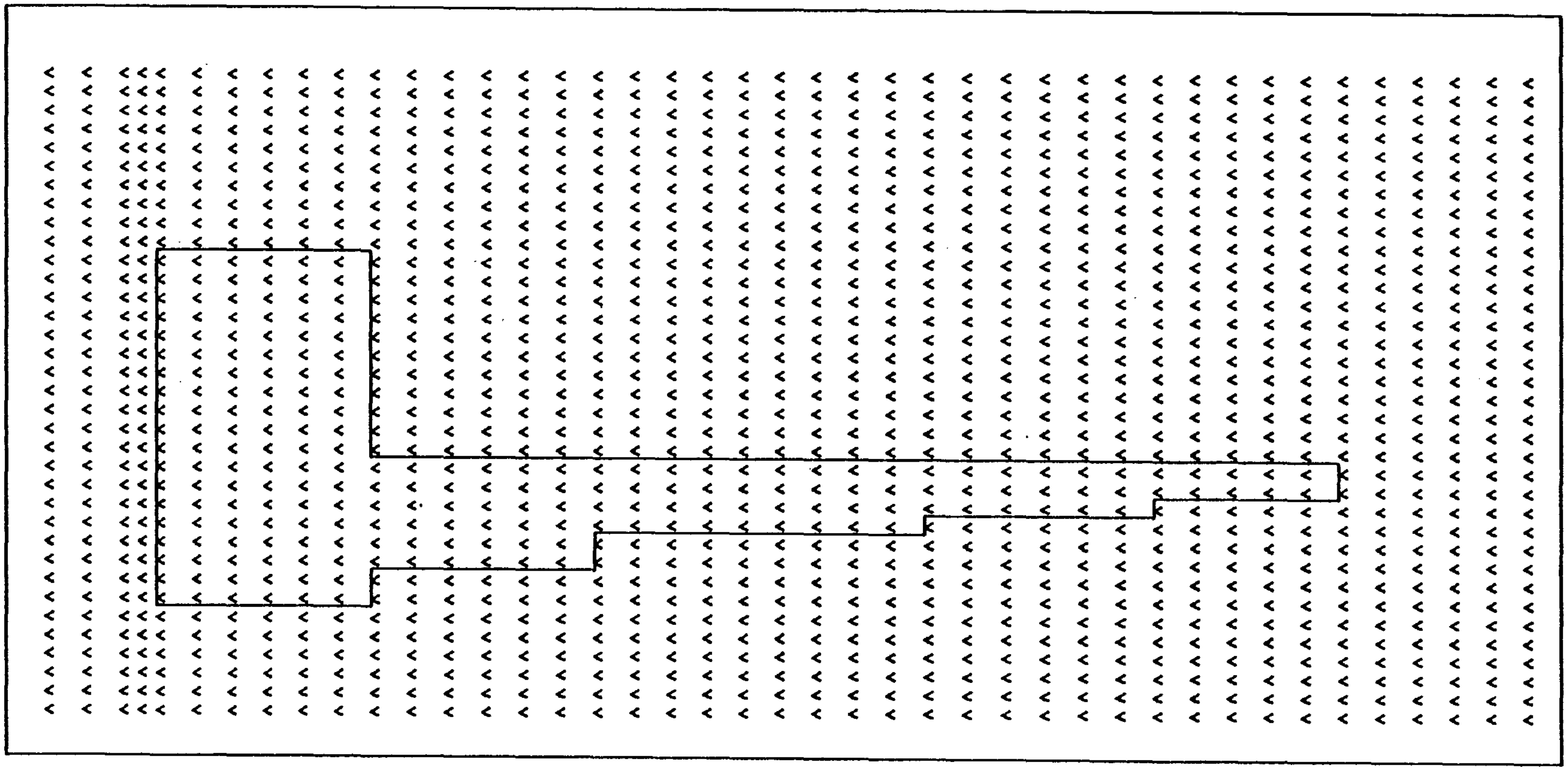
TIME (MIN) = 6.00

Figure E2-6-6: Simulated freezing progression map for stepped plate casting, time = 6 min.



TIME (MIN) = 9.00

Figure E2-6-7: Simulated freezing progression map for stepped plate casting, time = 9 min.



TIME (MIN) = 12.00

Figure E2-6-8: Simulation temperature map for test casting centerline time = 12 min.

E2-6-3 Cooling (and Heating) Curves: S

The routine S. FOR has been used to produce cooling curves for selected nodes in the casting and riser and heating curves for nodes in the sand, Figures E2-6-9 through E2-6-16. Refer to Figure E2-6-3 for location of the nodes. Figures E2-6-9 through E2-6-14, nodes within the casting, indicate solidification times between 10 and 15 minutes and show slower cooling through the solidification range. This slower cooling is caused by the liberation of latent heat during solidification. Figures E2-6-15 and E2-6-16 show the heating of the sand, especially for points near the metal.

E2-6-4 Cooling Rates: RATES

Using RATES. FOR the cooling rates for selected nodes within the casting where computed and the results are presented in Figures E2-6-17 through E2-6-22. These figures illustrate the decrease in cooling rate that occurs within the solidification range. The variation of cooling rate for different locations is also indicated.

E2-6-5 Temperature Distribution: TEMPOS

The variation of temperature with respect to position was selected for plotting by TEMPOS. FOR and the plots are presented in Figures E2-6-23 through E2-6-30 for parts of the riser and plate casting Figures E2-6-31 through E2-6-34 relate to variations of temperature within the sand. These graphs show plots at each time interval. Three things can be noted from the figures. There are steep thermal gradients in the sand near the metal/sand interface, little temperature variation of the metal in the vertical direction, and significant temperature variation along the horizontal direction of the casting.

E2-6-6 Temperature Gradients: GRAD

The temperature gradients at selected nodes were computed at several time steps using GRAD. FOR. The results are presented in Figure E2-6-35. These values related directly to the ability to feed solidification shrinkage and as a result the soundness of the casting as determined by radiogrpahic standards.

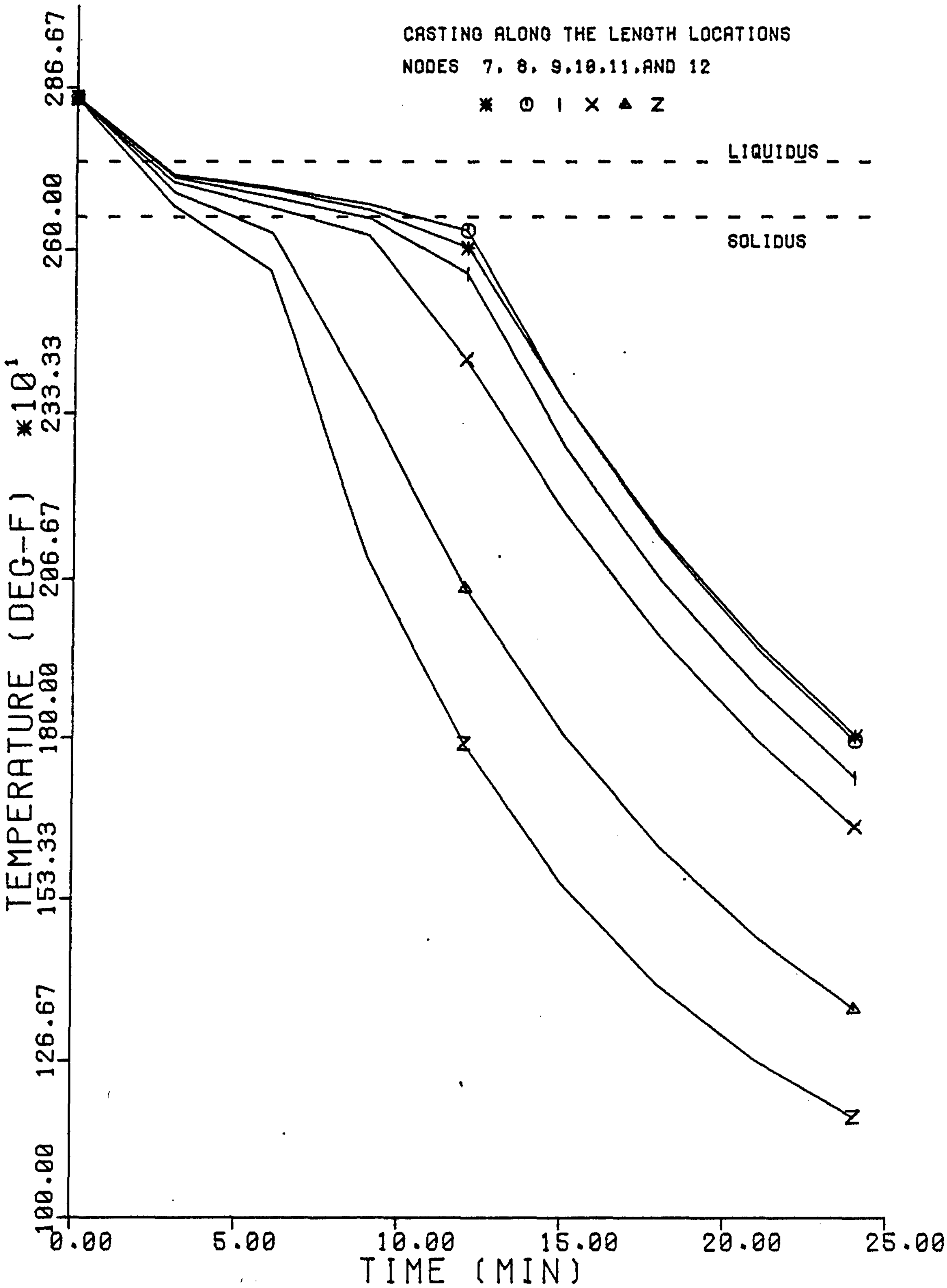


Figure E2-6-9: Simulation cooling curves for casting along the length.

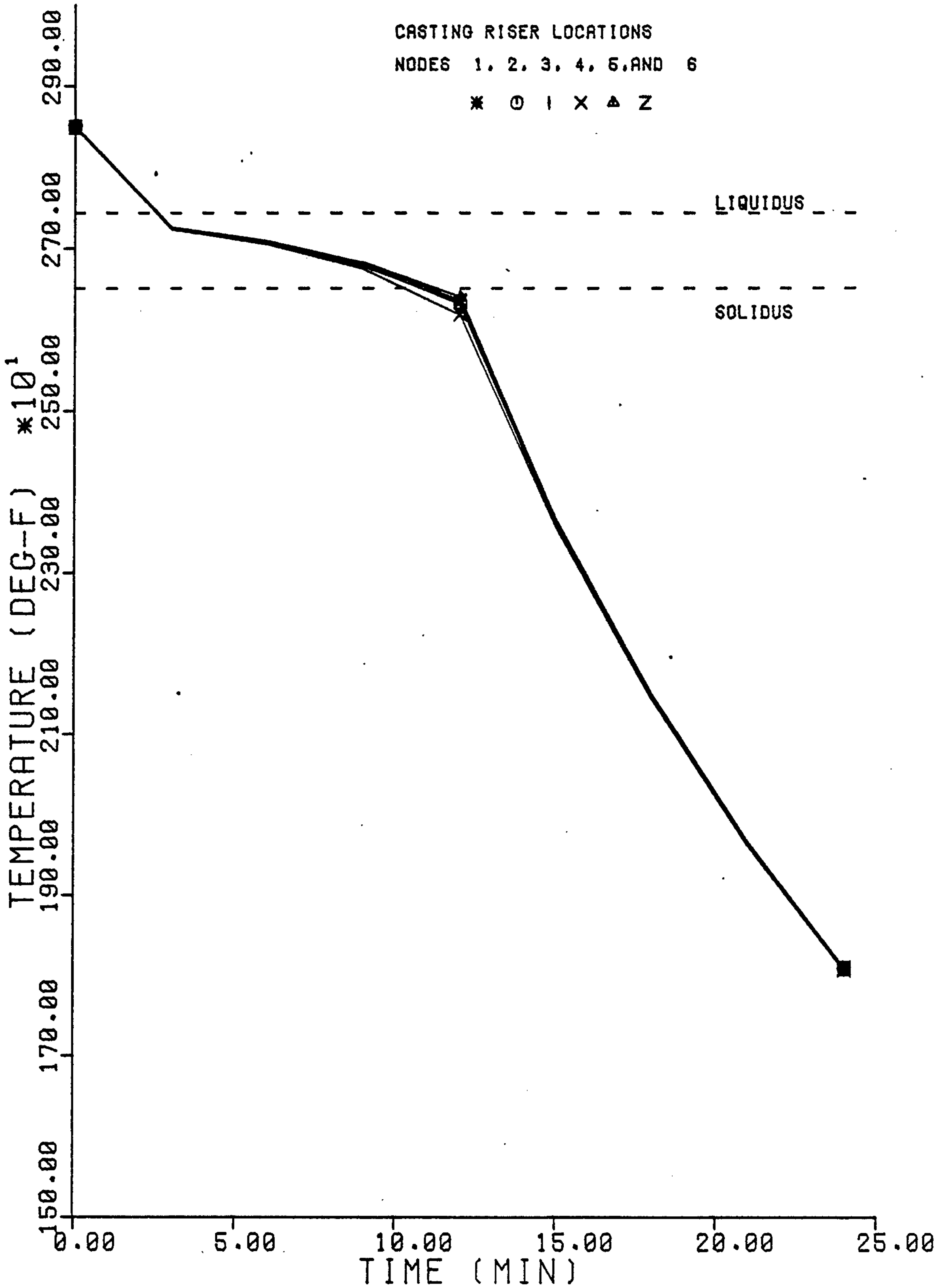


Figure E2-6-10: Simulation cooling curves for casting in the riser.

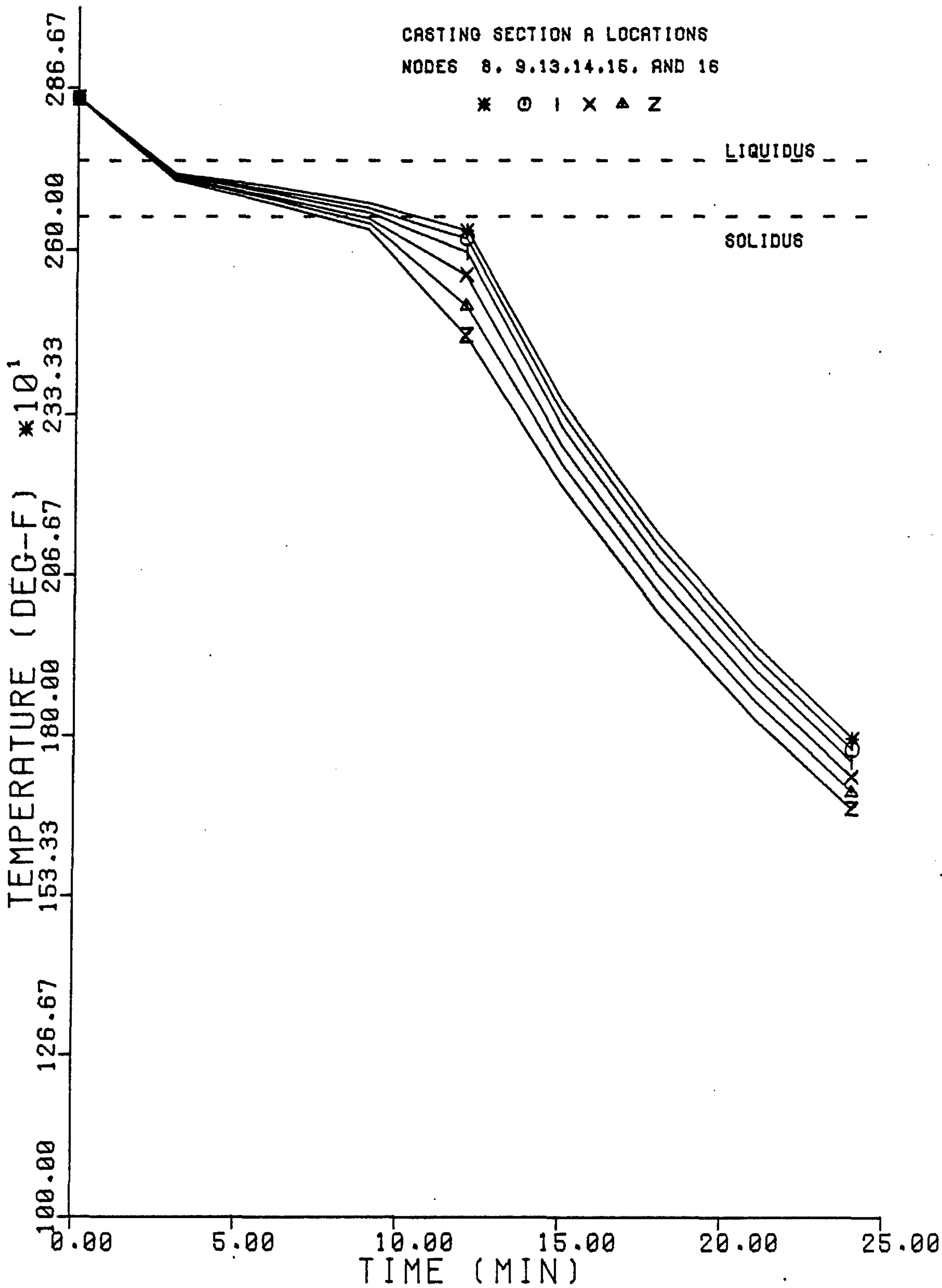


Figure E2-6-11: Simulation cooling curves for casting in section A.

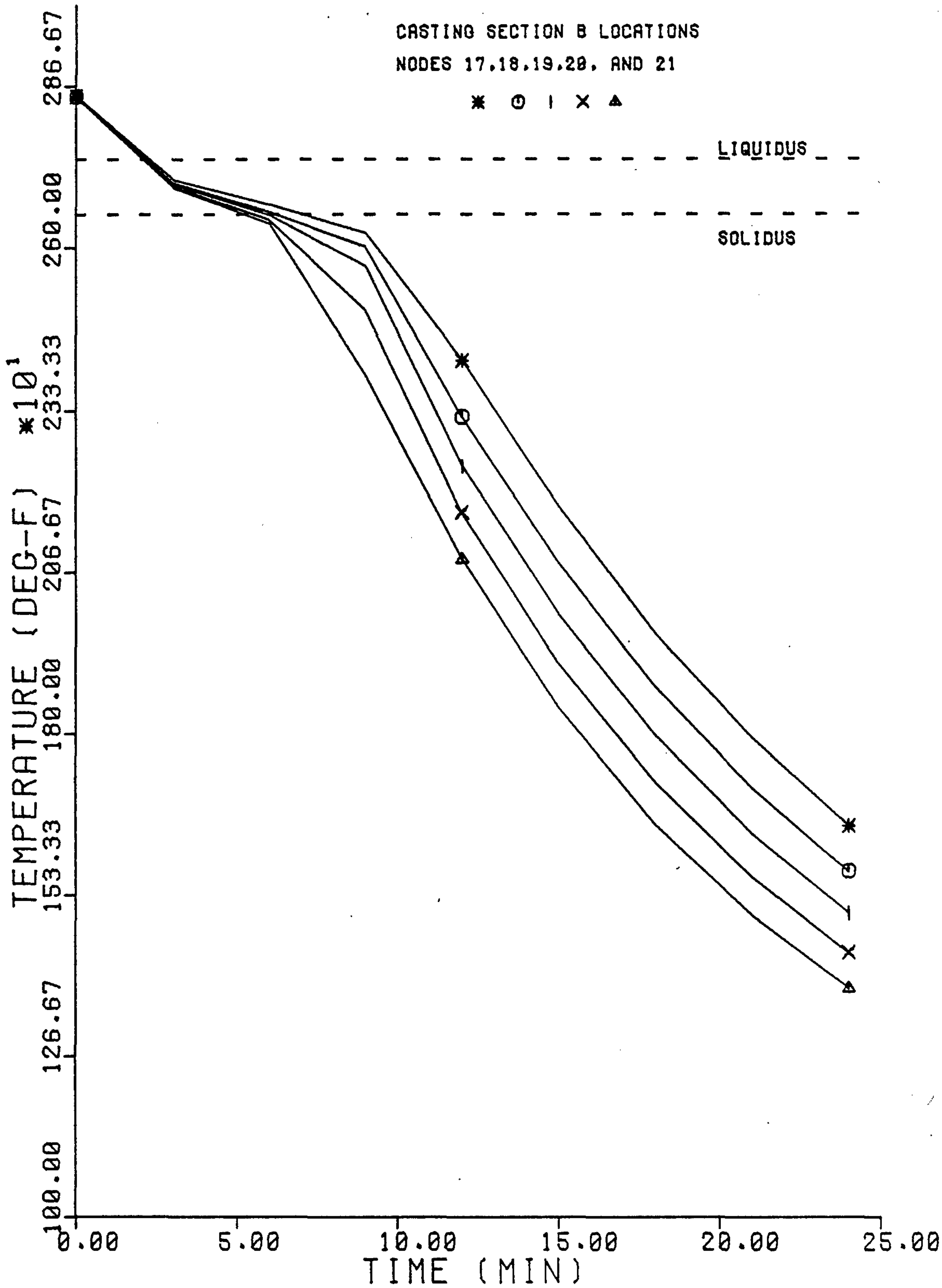


Figure E2-6-12: Simulation cooling curves for casting in section B.

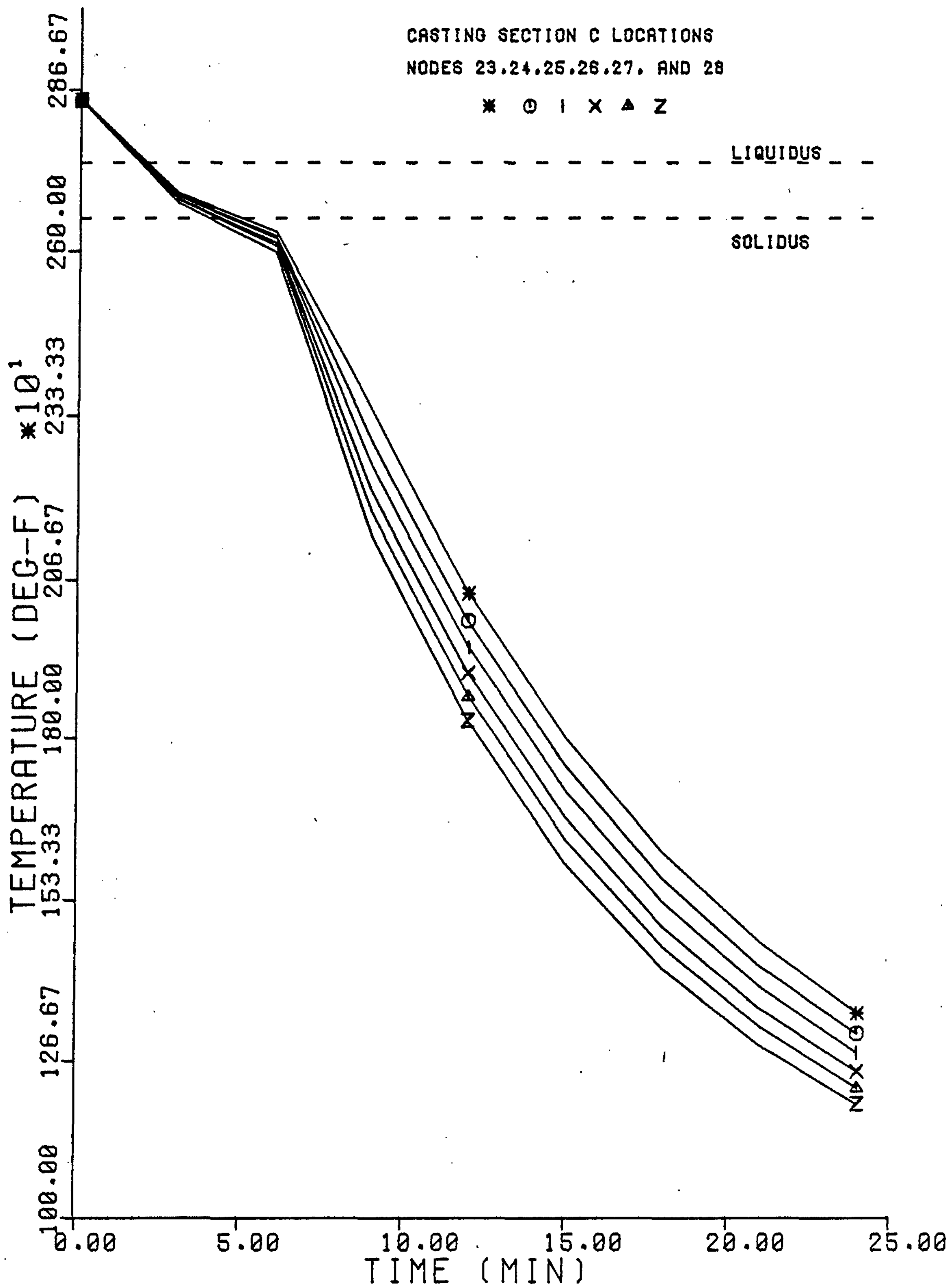


Figure E2-6-13: Simulation cooling curves for casting in section C.

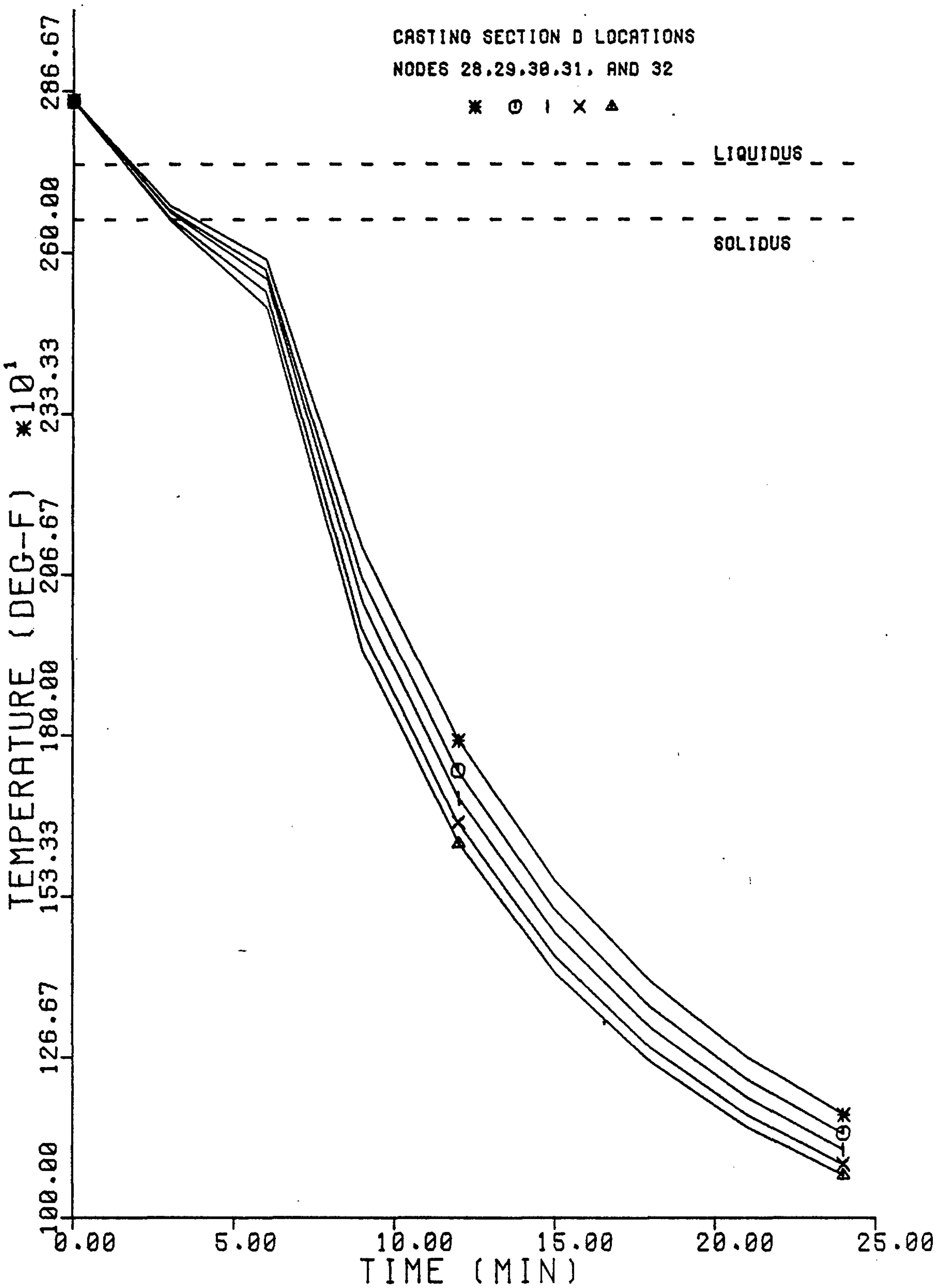


Figure E2-6-14: Simulation cooling curves for casting in section D.

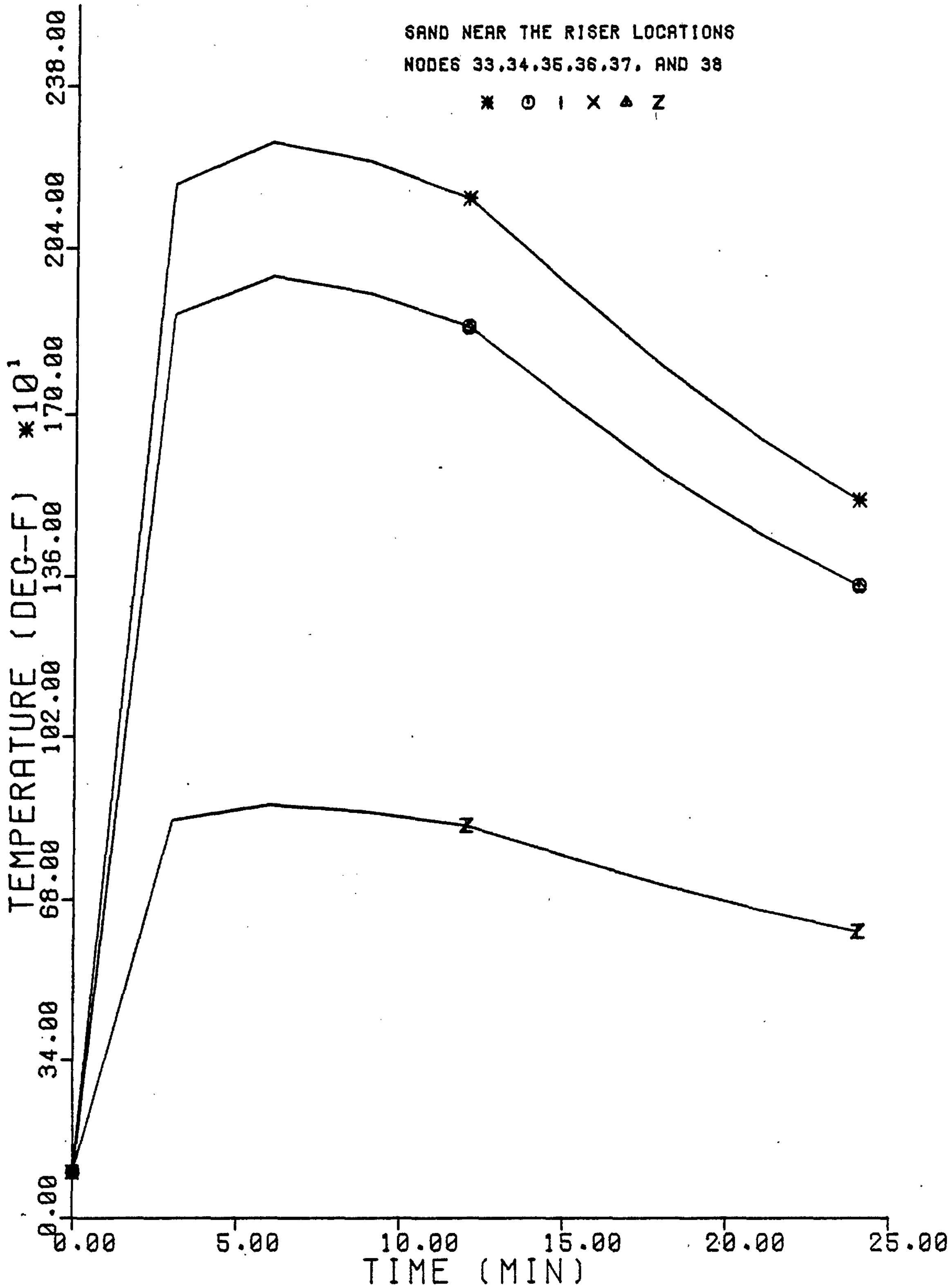


Figure E2-6-15: Simulation cooling curves for sand near the riser.

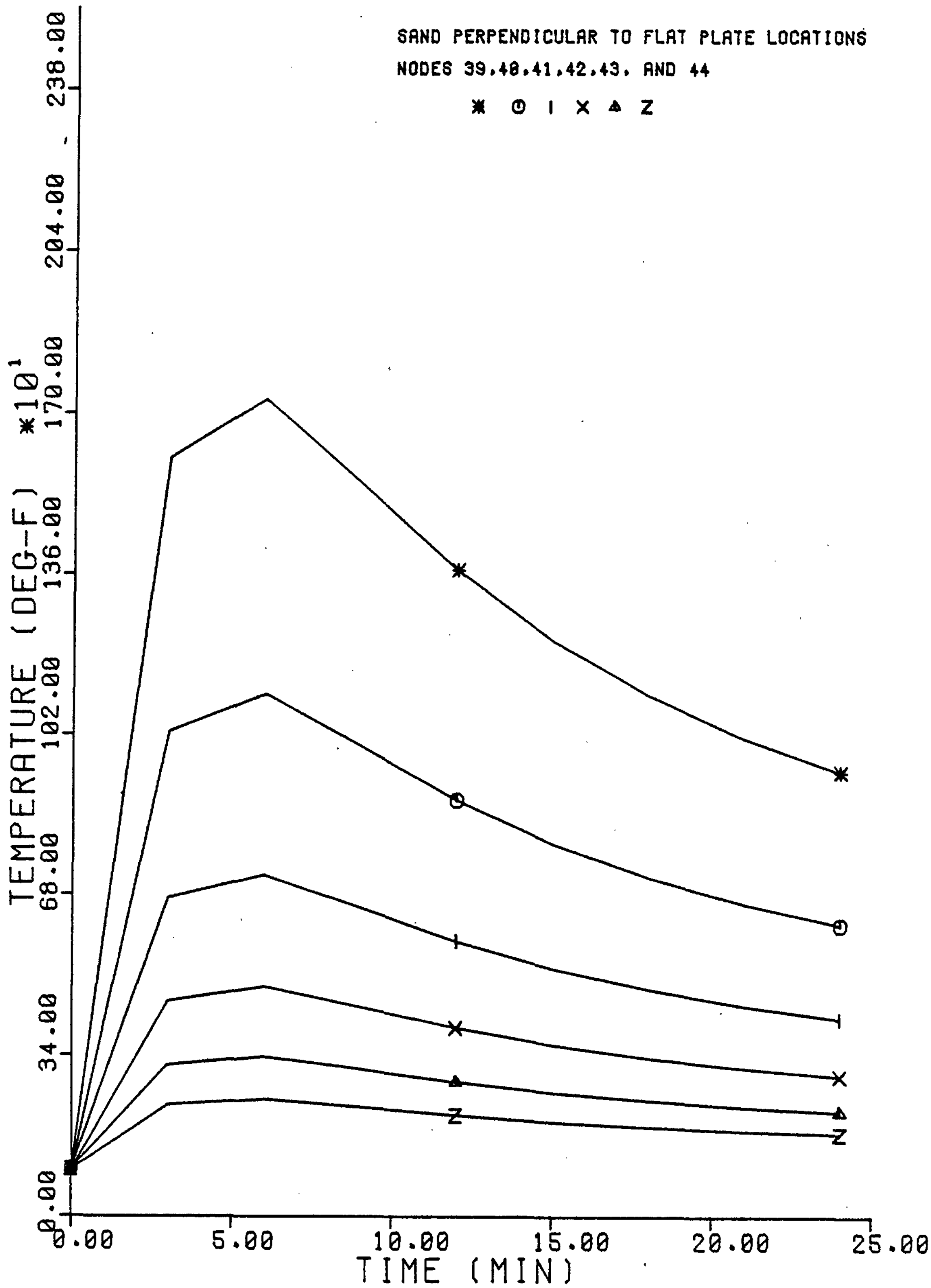


Figure E2-6-16: Simulation cooling curves for sand near the flat plate.

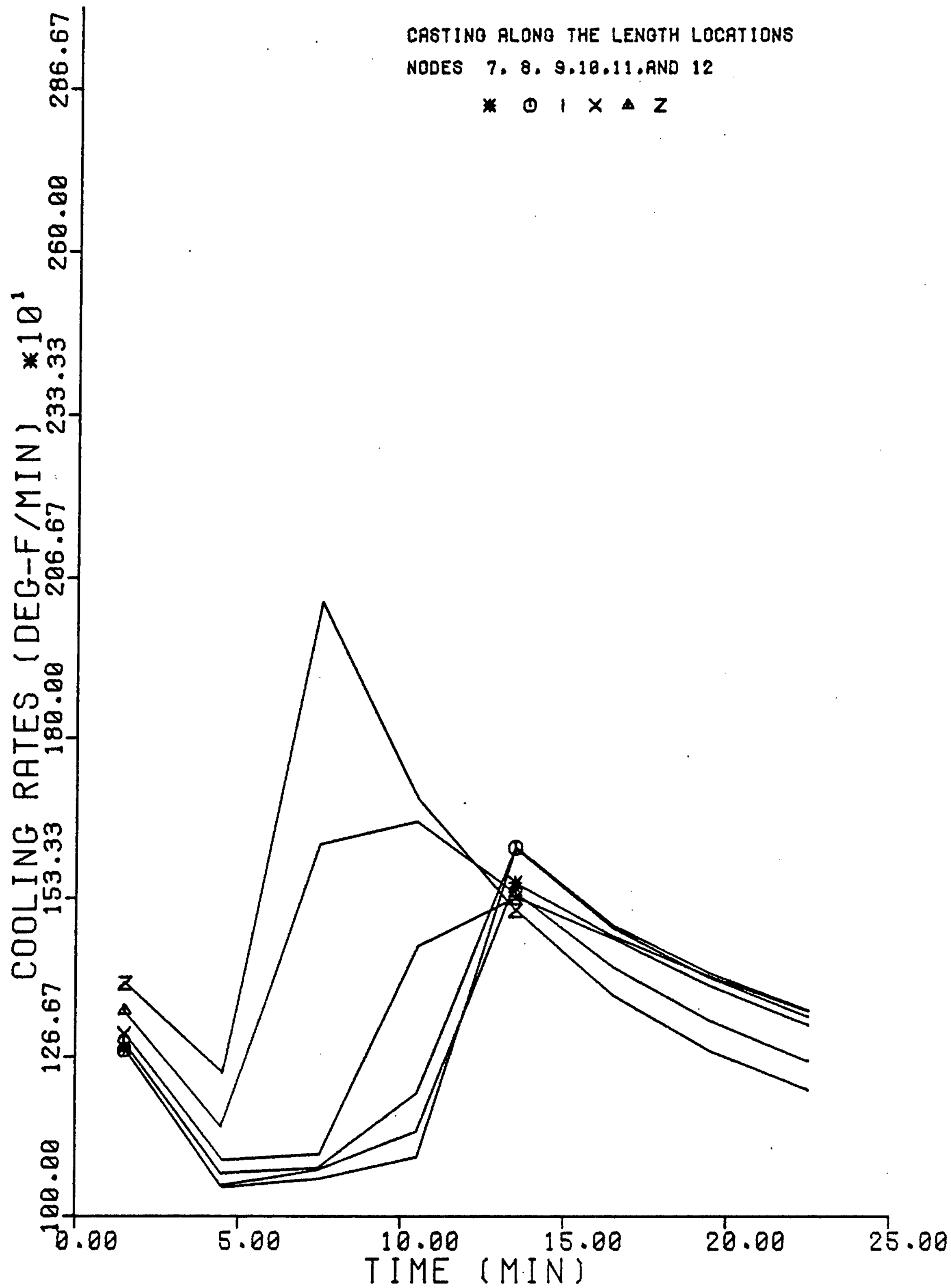


Figure E2-6-17: Simulation cooling rates for casting along the length.

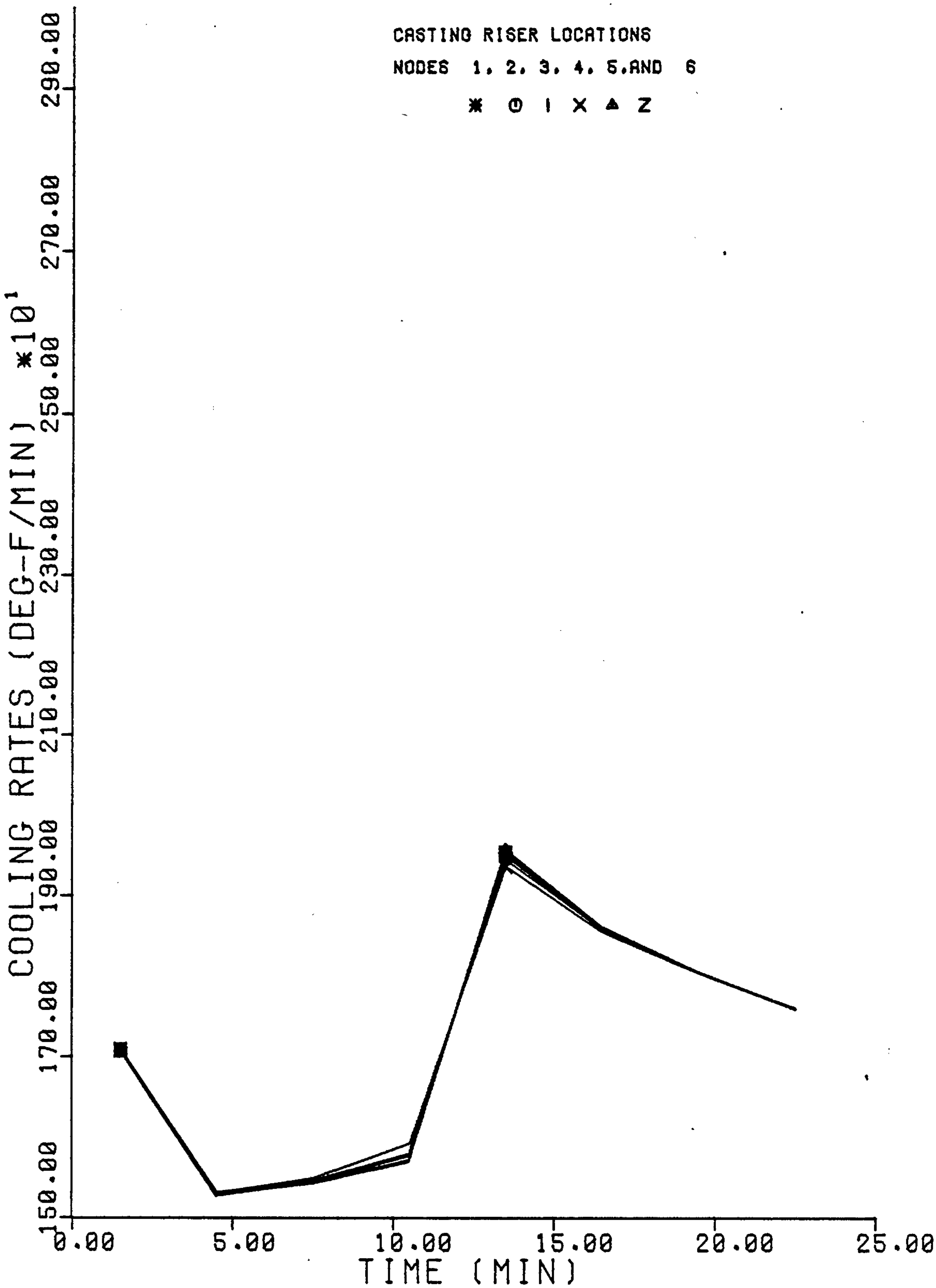


Figure E2-6-18: Simulation cooling rates for casting in the riser.

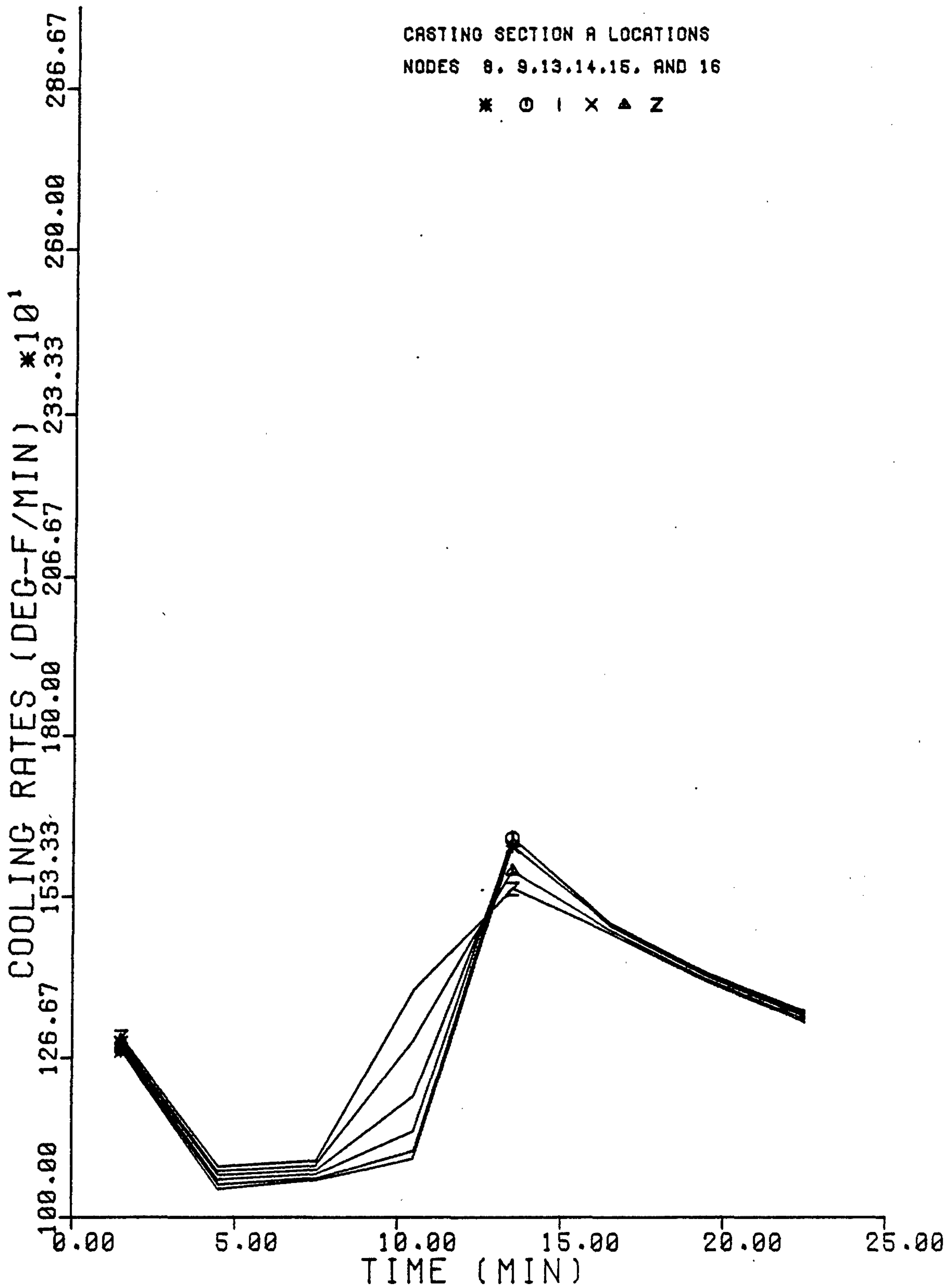


Figure E2-6-19: Simulation cooling rates for casting in section A.

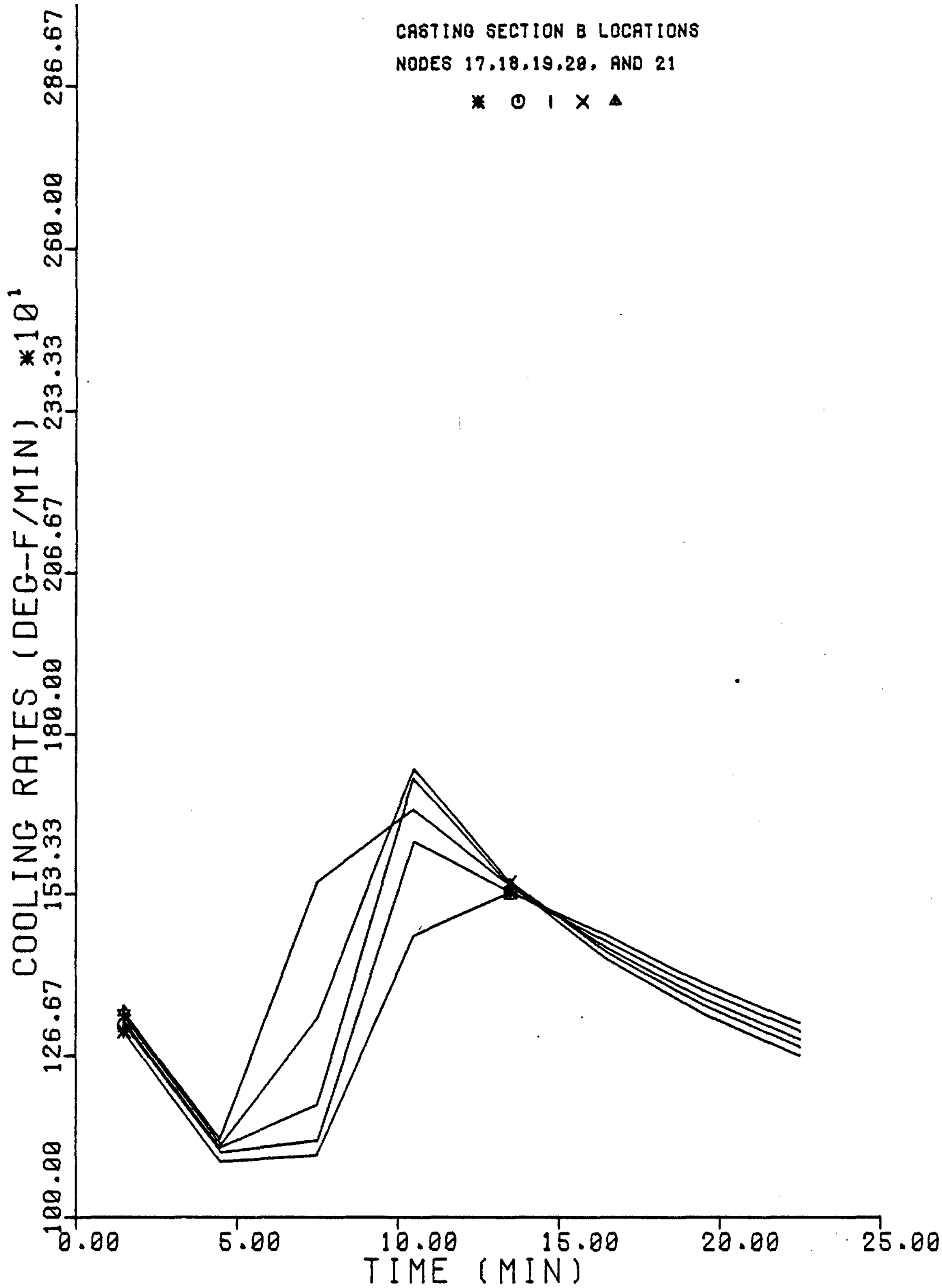


Figure E2-6-20: Simulation cooling rates for casting in section B.

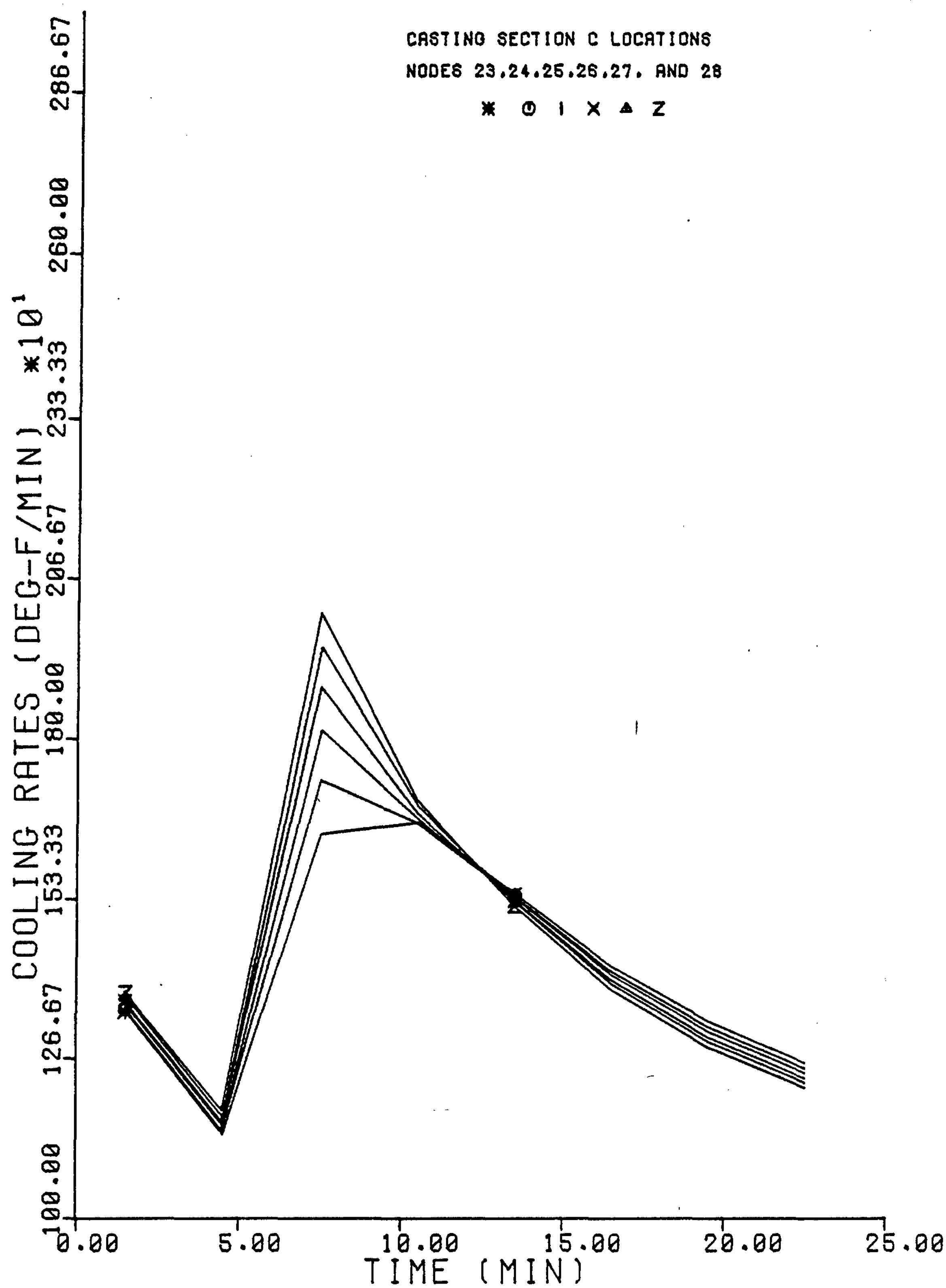


Figure E2-6-21: Simulation cooling rates for casting in section C.

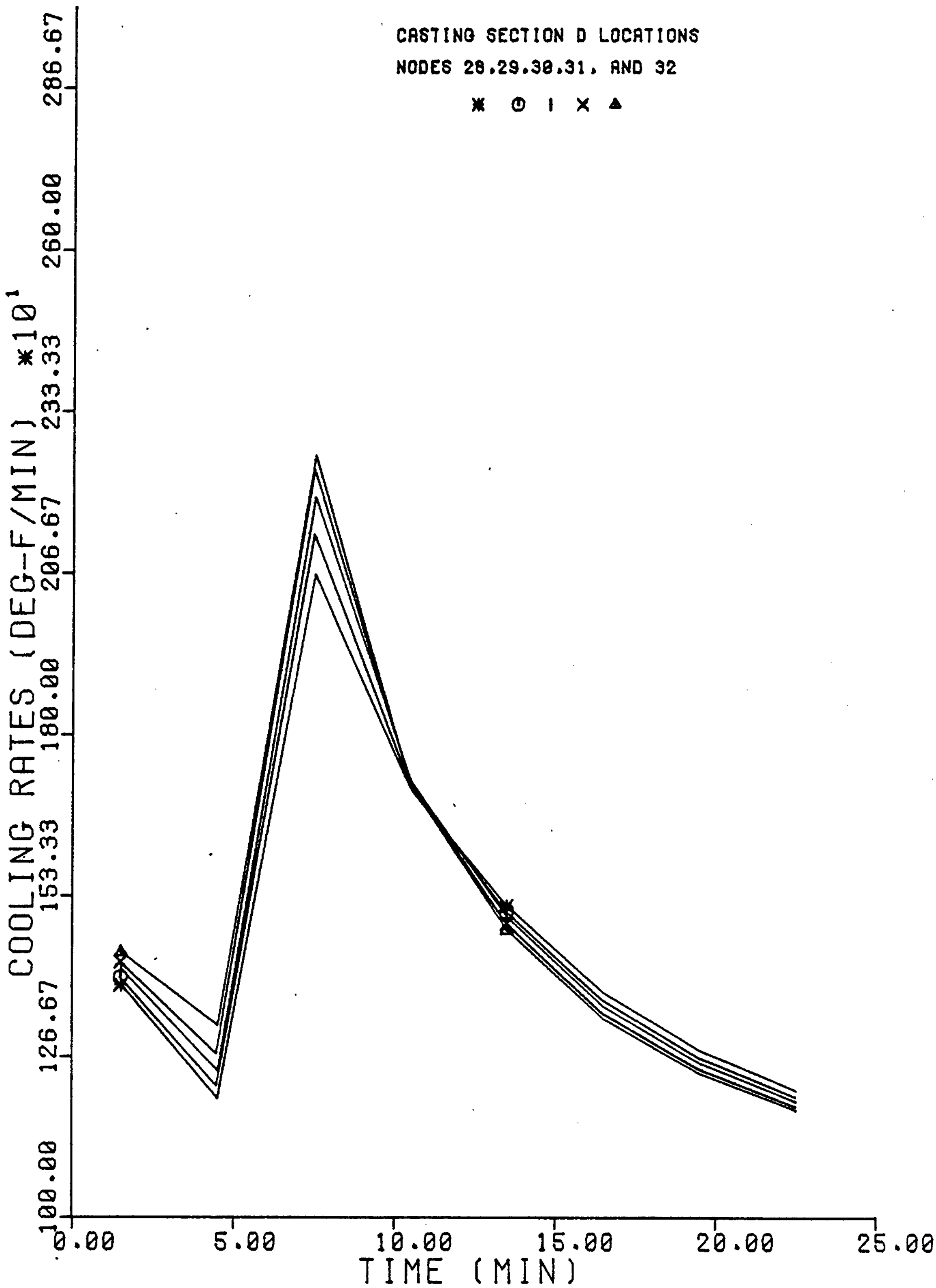


Figure E2-6-22: Simulation cooling rates for casting in section D.

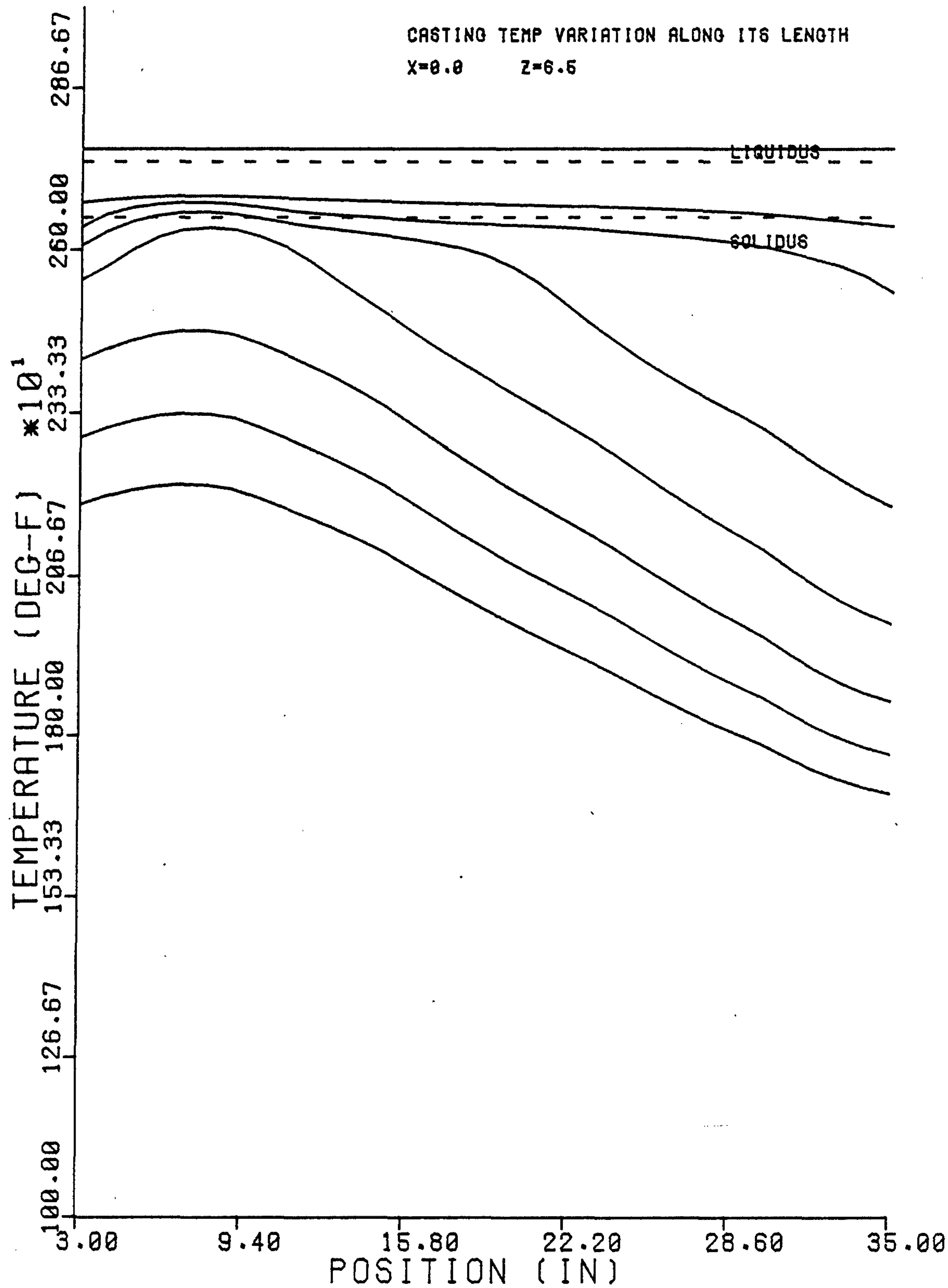


Figure E2-6-23: Simulation temperature distribution history for casting along the length.

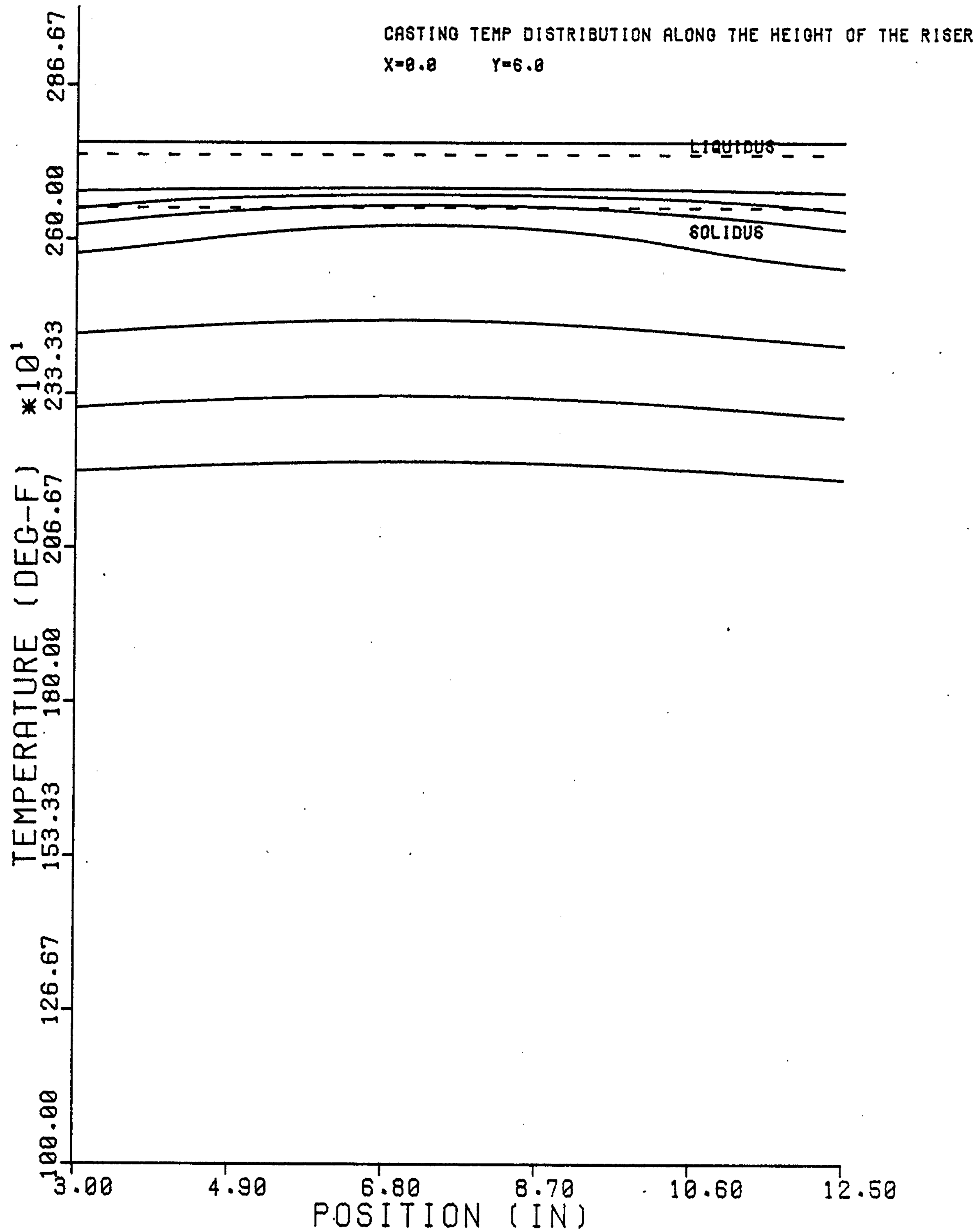


Figure E2-6-24: Simulation temperature distribution history for riser with height.

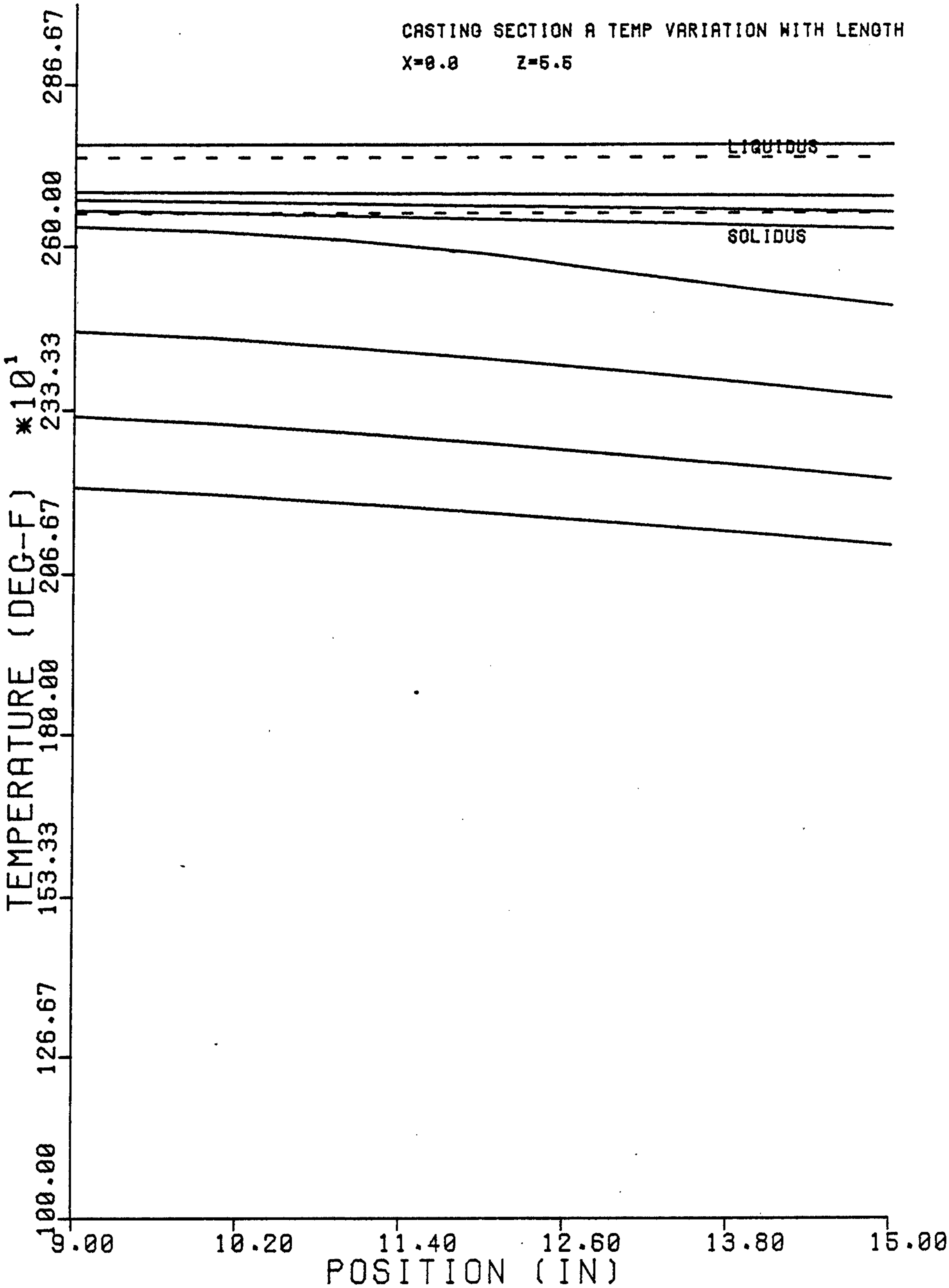


Figure E2-6-25: Simulation temperature distribution history of section A along length.

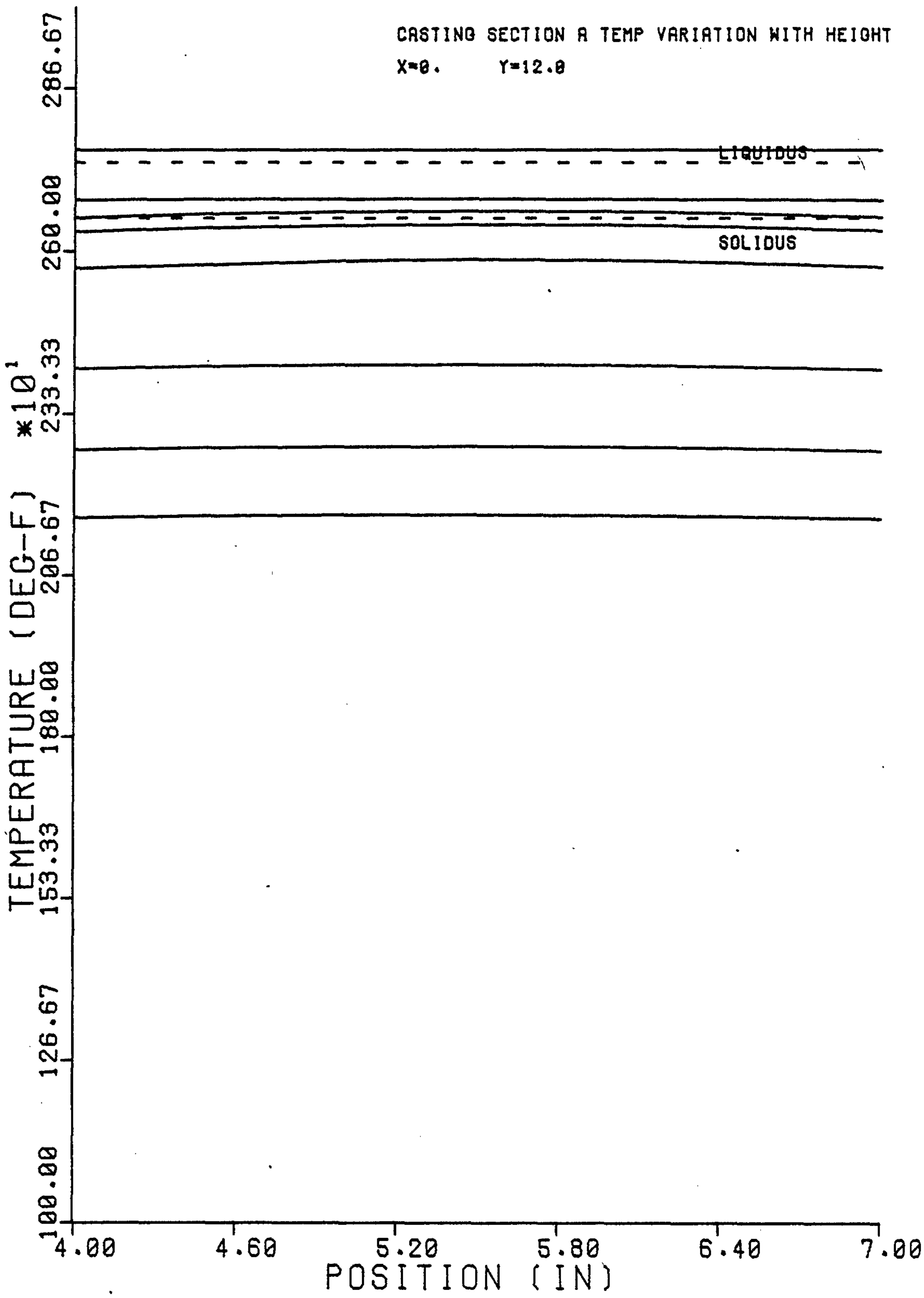


Figure E2-6-26: Simulation temperature distribution history for section A with height.

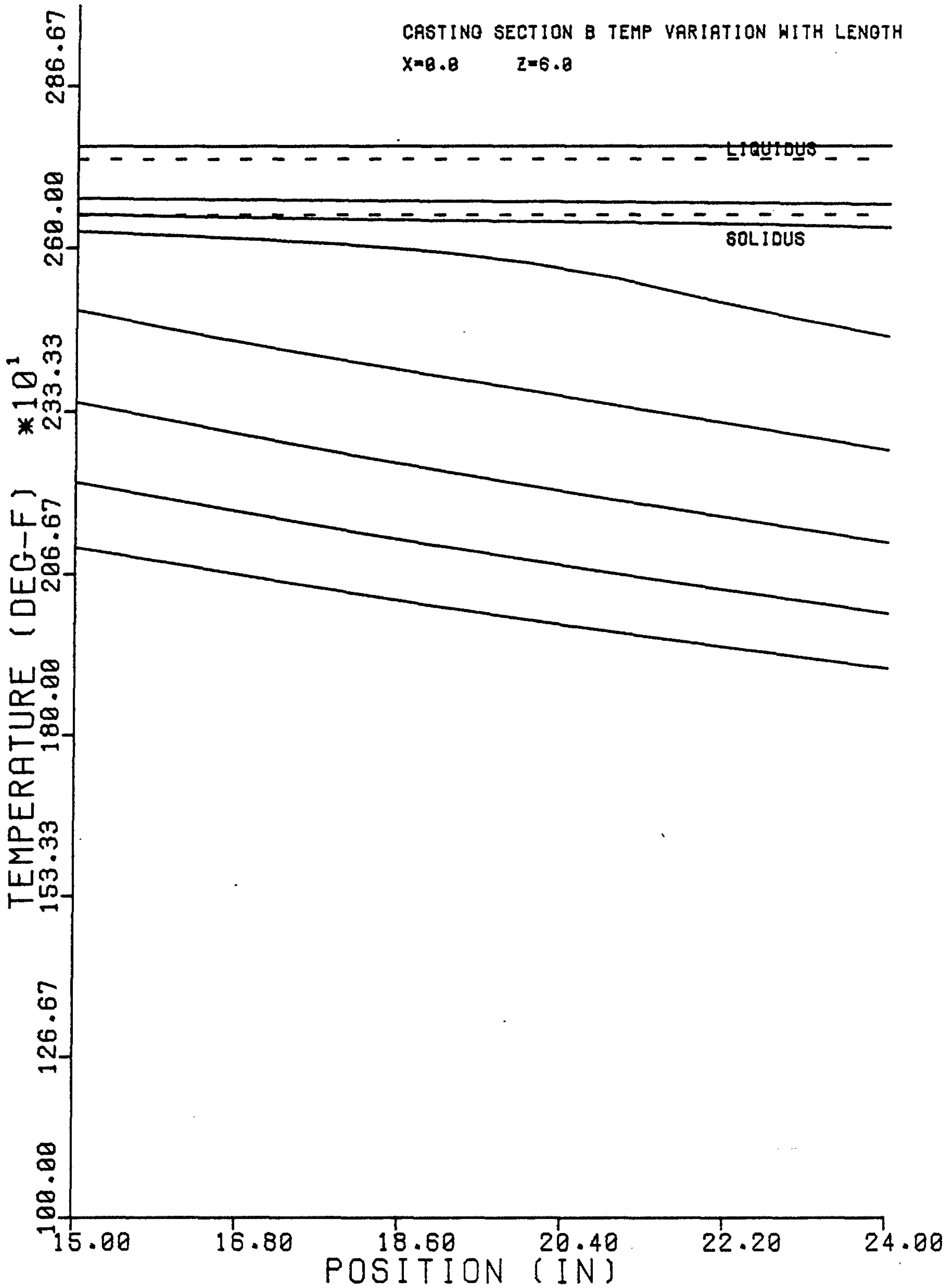


Figure E2-6-27: Simulation temperature distribution history for section B along length.

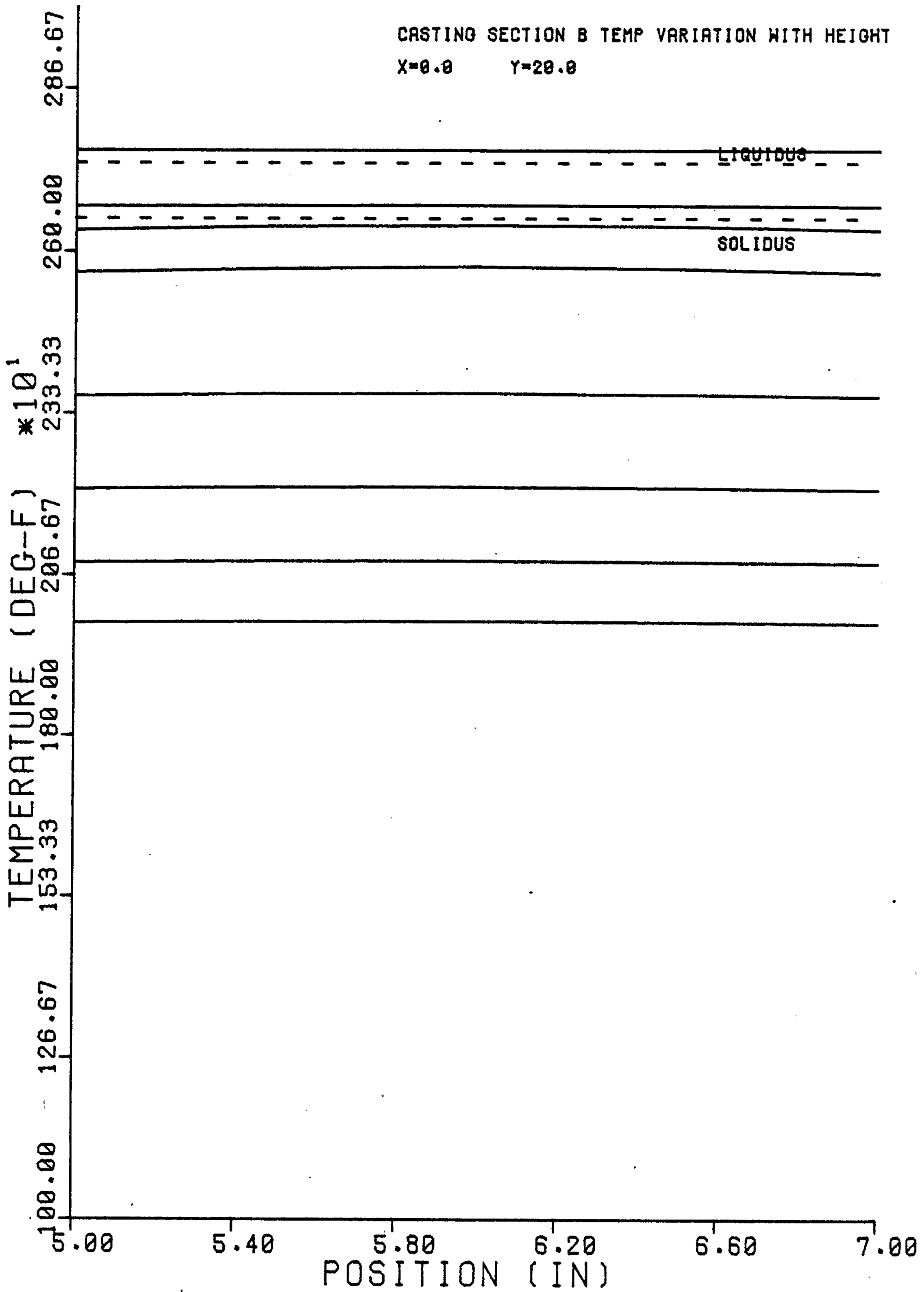


Figure E2-6-28: Simulation temperature distribution history for section B with height.

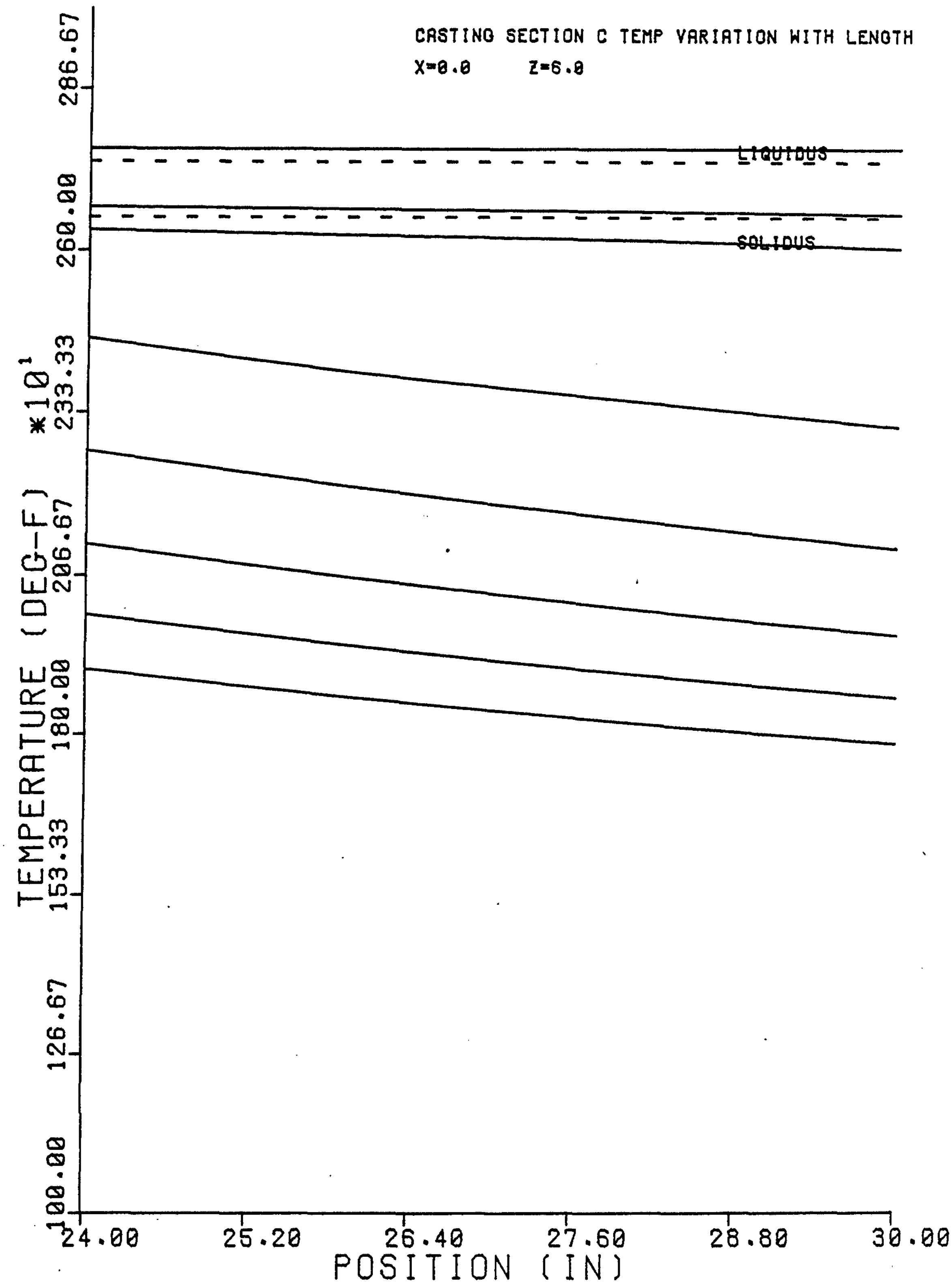


Figure E2-6-29: Simulation temperature distribution history for section C along length.

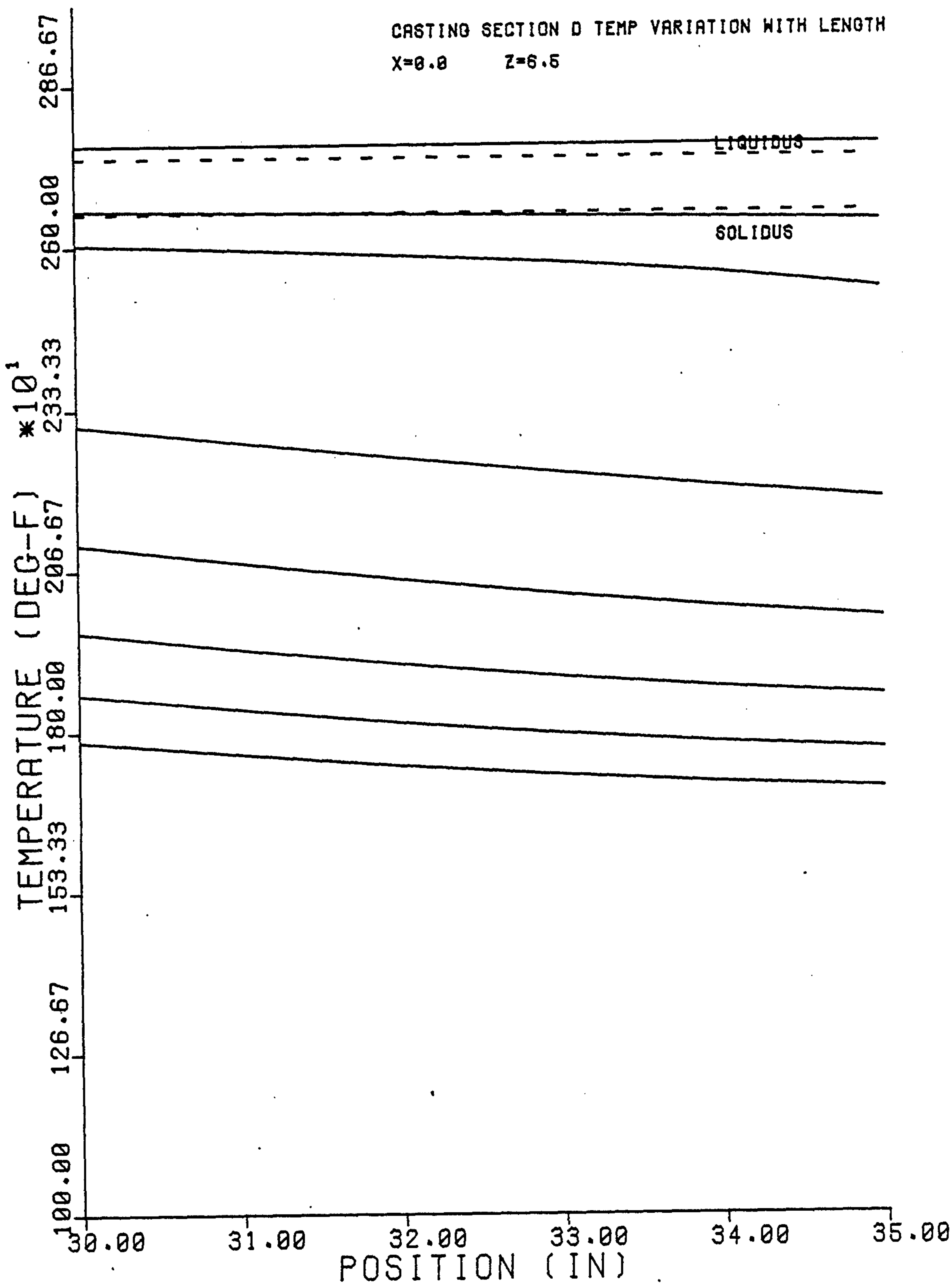


Figure E2-6-30: Simulation temperature distribution history for section D along length.

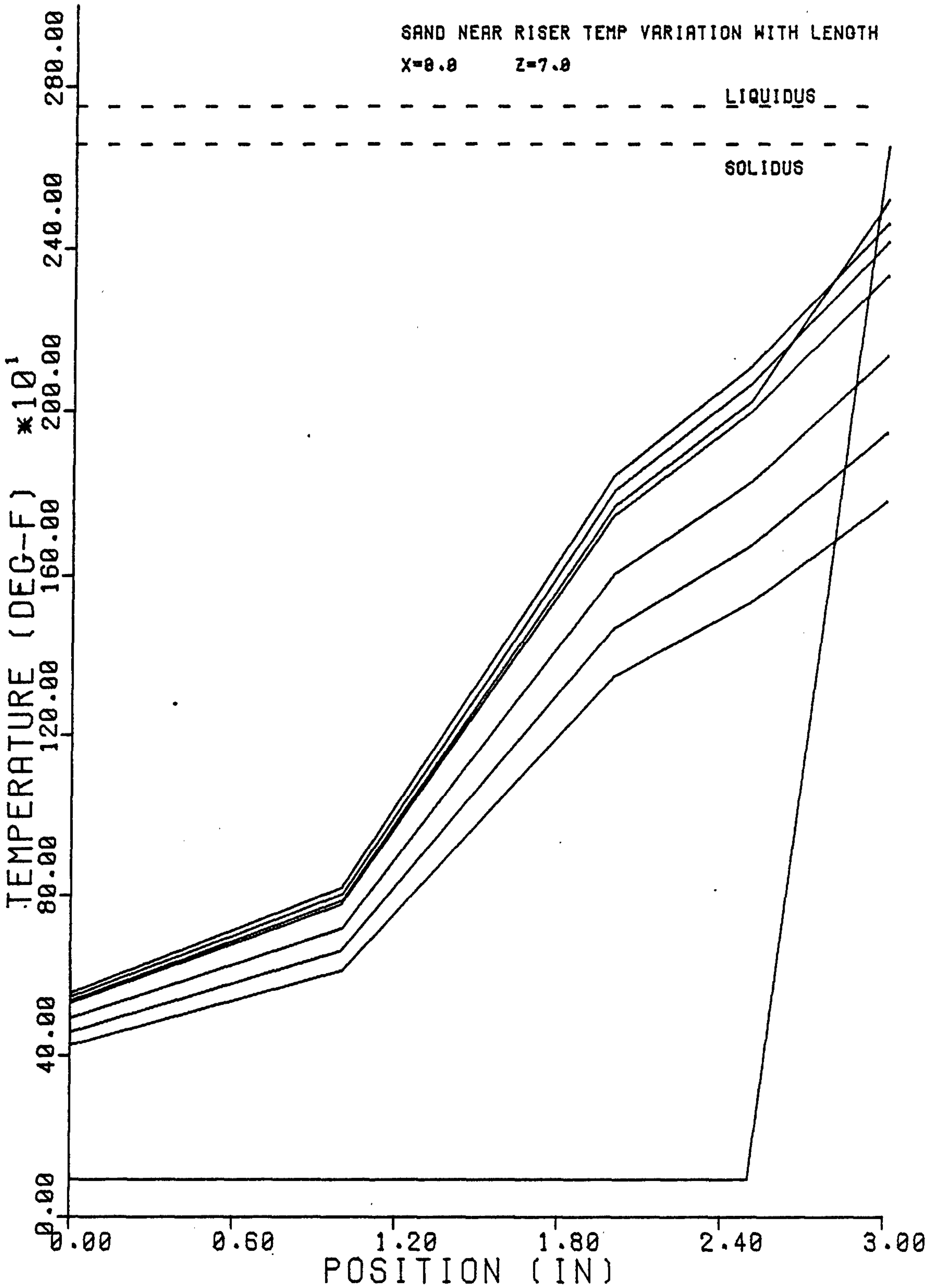


Figure E2-6-31: Simulation temperature distribution history for sand near riser along length.

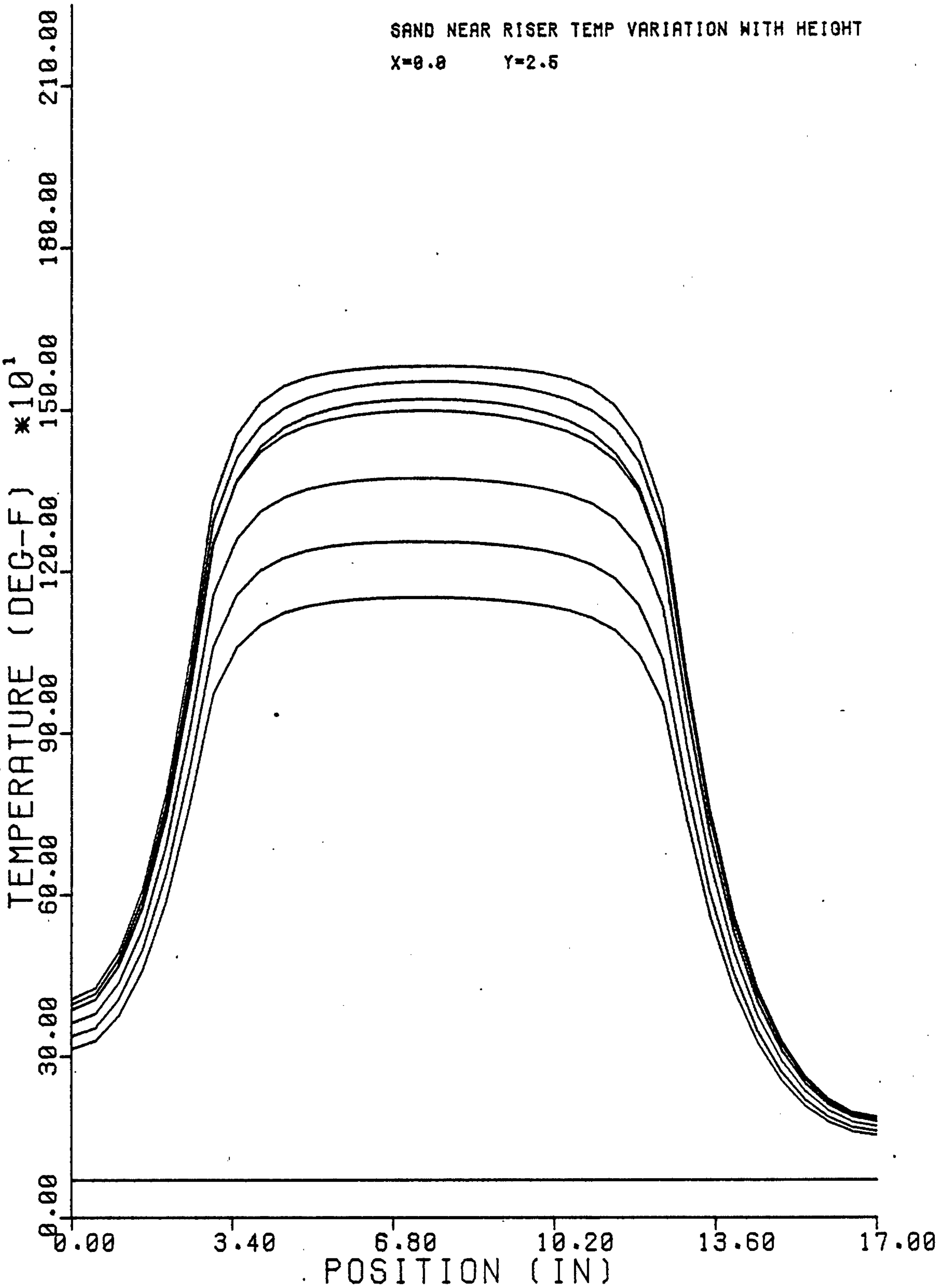


Figure E2-6-32: Simulation temperature distribution history for sand near riser along length.

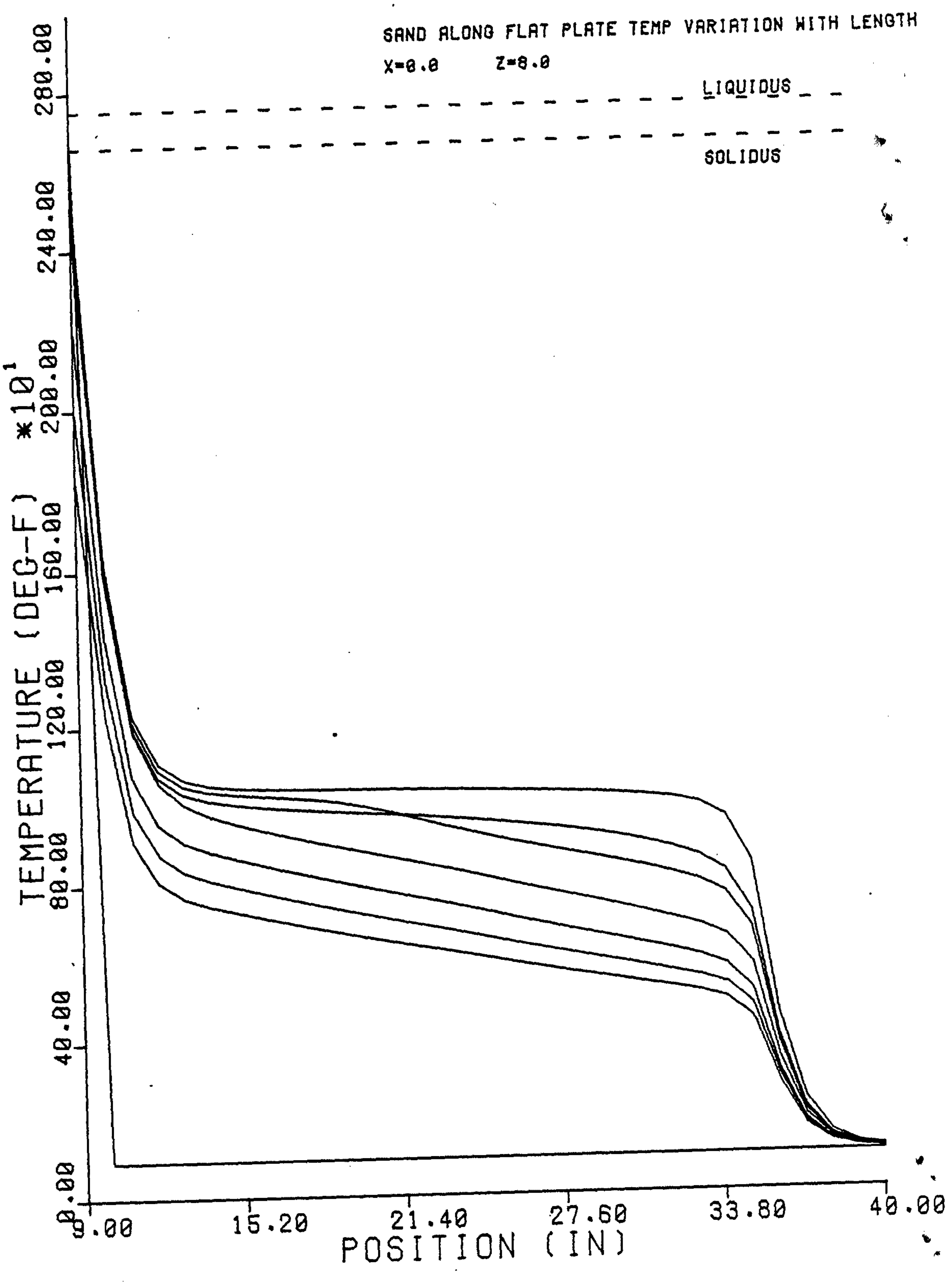


Figure E2-6-33: Simulation temperature distribution history for sand near flat plate along length.

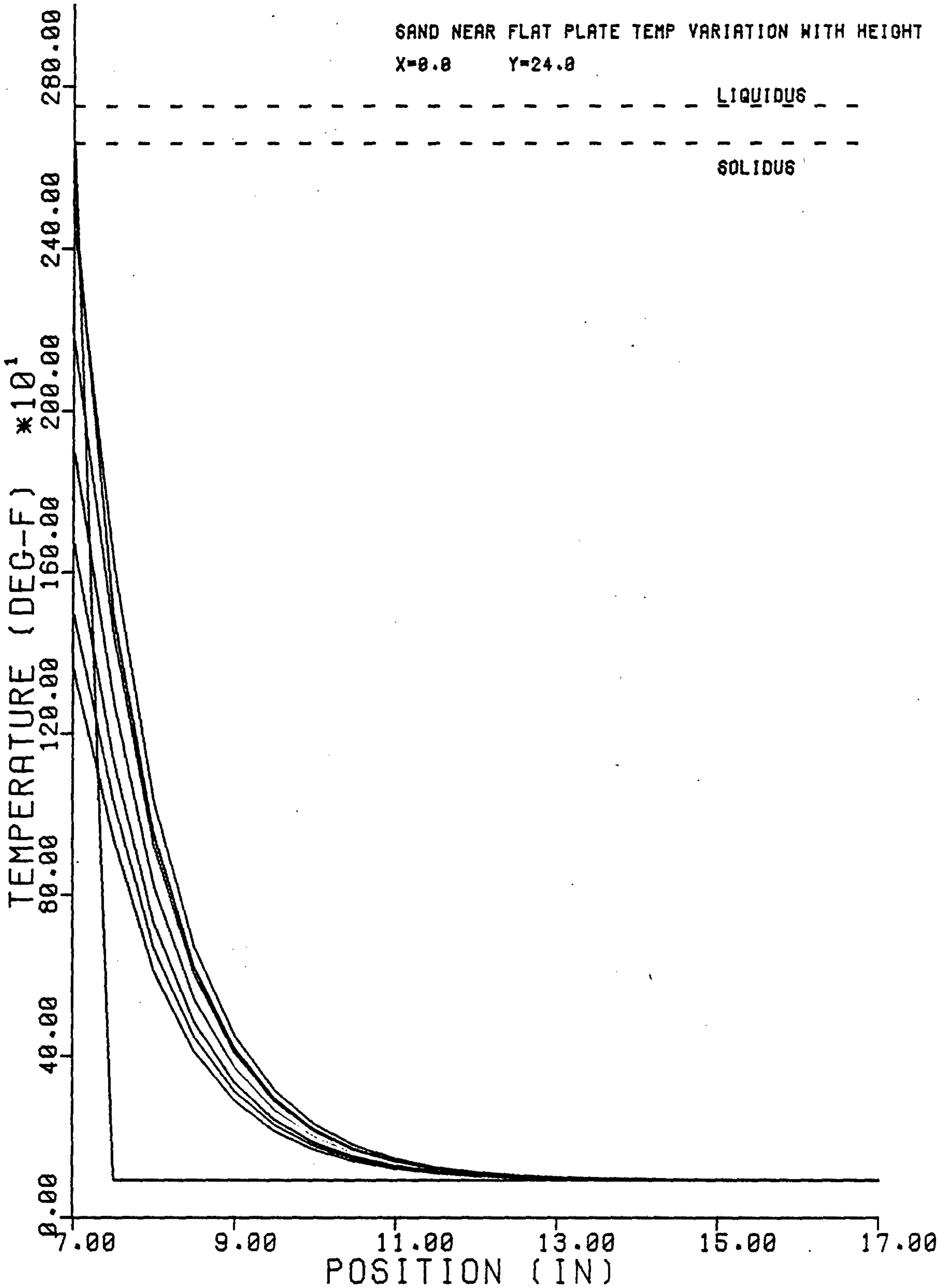


Figure E2-6-34: Simulation temperature distribution history for sand near flat plate with height.

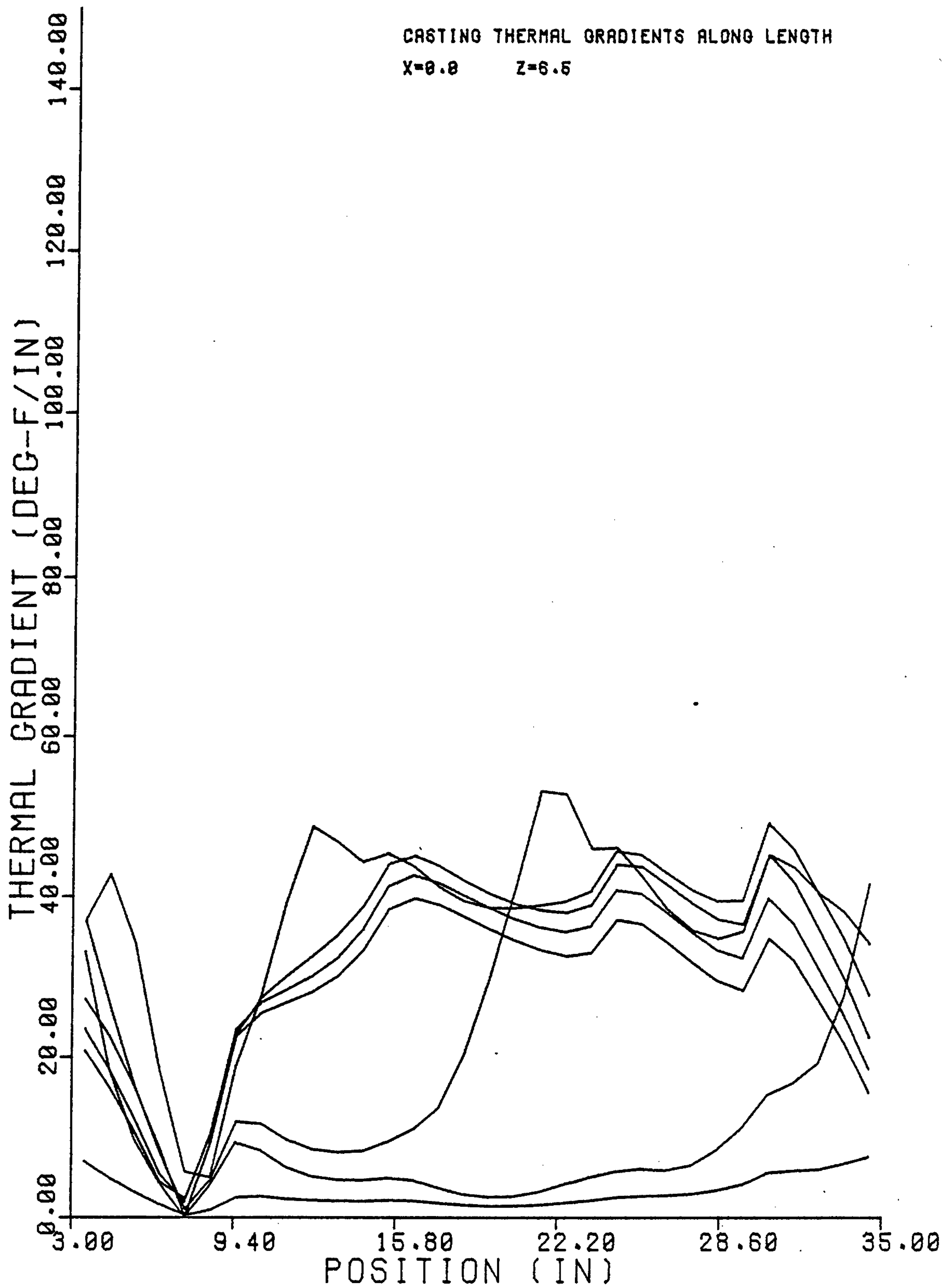


Figure E2-6-35: Simulation thermal gradients in steel at various times.

APPENDIX A

BRIEF DOCUMENTATION OF CSSP

BRIEF DOCUMENTATION,CSSP

****

CASTING SOLIDIFICATION SIMULATION PROGRAM

****

THE FOLLOWING BRIEF INSTRUCTIONS ARE INTENDED TO GUIDE THE INITIAL USE OF THE CASTING SOLIDIFICATION SIMULATION PROGRAM (CSSP) AND ASSOCIATED ROUTINES. CSSP IS A FINITE ELEMENT HEAT TRANSFER PROGRAM TO SIMULATE THE BEHAVIOR OF AN INITIALLY MOLTEN ALLOY IN A SAND MOLD. THE GEOMETRY OF THE CASTING SIMULATED BY CSSP MAY BE ANY 3-D SHAPE. HOWEVER, IF THE SEMI-AUTOMATIC MESH GENERATION ROUTINE, AGRID, IS USED, THE GEOMETRIC CAPABILITIES ARE LIMITED AS DESCRIBED BELOW.

****

THE NORMAL STEPS IN A SIMULATION ARE

1. DEFINE (BY HAND ON SCRATCH PAPER) THE PROBLEM PARAMETERS:

(A) CASTING AND MOLD GEOMETRY AND FINITE ELEMENT MESH
(B) THERMAL PROPERTIES
(C) TIME STEP

2. CREATE AN INPUT FILE -- AGRID MAY BE USED

3. RUN THE SIMULATION PROGRAM -- CSSP

(A) TIME SHARING EXECUTION
(B) BATCH EXECUTION

4. PROCESS OUTPUT DATA

****

1. DEFINE THE PROBLEM PARAMETERS

(A) CASTING GEOMETRY AND FINITE ELEMENT MESH

THE GEOMETRY OF THE PROBLEM, I.E. THE CASTING CAVITY INCLUDING THE RISERS AND THE MOLD WITHIN THE FLASK (OR CORE BOX) BOUNDARIES, AND THE MESH INFORMATION ARE REQUIRED INPUT INFORMATION FOR CSSP.

THIS DATA CAN BE INPUT INTO A FILE BY EXECUTING AGRID. THIS METHOD REQUIRES THE USER TO DRAW THE MESH BY HAND AND, THEN, INTERACTIVELY CREATE THE MESH FILE USING THE FACILITIES OF AGRID. FOR USE WITH AGRID THE HAND DRAWN MESH IS LIMITED TO CONTAIN BRICK ELEMENTS ONLY. (CSSP CAN HANDLE TETRAHEDRAL AND WEDGE ELEMENTS AS WELL AS BRICK ELEMENTS. CREATION OF A FILE CONTAINING THESE ELEMENTS WOULD REQUIRE A MESH GENERATION ROUTINE OTHER THAN AGRID.) THE CASTING CAVITY MAY BE DEFINED BY A MAXIMUM OF FIVE BRICK SHAPES. THE CASTING MUST FIT INSIDE A BRICK SHAPED FLASK. THE SKETCH SHOULD BE DRAWN WITH REFERENCE TO AN X,Y,Z COORDINATE SYSTEM. COORDINATES OF ALL POINTS DO NOT HAVE TO BE DETERMINED IN PREPARATION FOR AGRID, HOWEVER, COORDINATES OF KEY POINTS SHOULD BE KNOWN BEFORE USING AGRID. THE FINITE ELEMENT MESH SHOULD HAVE THE SMALLEST ELEMENTS - CLOSEST NODE SPACING - IN REGIONS OF HIGHEST EXPECTED TEMPERATURE GRADIENT, E.G. IN THE SAND AT THE SAND/ALLOY INTERFACE.

ALTERNATIVELY, THE PROBLEM GEOMETRY AND FINITE ELEMENT MESH FILE MAY BE CREATED BY HAND, A TEDIOUS TASK, AND PREPARED IN THE FORMAT REQUIRED BY CSSP. A MORE ACCEPTABLE ALTERNATIVE WOULD BE TO USE AN INTERACTIVE COMPUTER GRAPHICS ROUTINE FOR MODEL AND MESH GENERATION, SUCH AS BCAST OR UNISTRUC. HOWEVER, THESE ROUTINES HAVE NOT BEEN INTERFACED WITH CSSP, YET. THE OUTPUT FILES OF THESE ROUTINES WOULD HAVE TO BE PROCESSED FURTHER TO MEET TO THE INPUT REQUIREMENTS OF CSSP. SEE SECTION EB-5 OF THE 1981 TACOM REPORT FOR THE PROPER FORMAT.

(B) MATERIAL PROPERTIES

CURRENTLY, MATERIAL PROPERTIES HAVE THEIR VALUES INITIALIZED IN CSSP AS DATA STATEMENTS. THE SYMBOLS FOR ALL MATERIALS PROPERTIES ARE DEFINED IN THE PROGRAM LISTING. THE CURRENT VALUES IN B.T.U.'S, FT., HR., DEG. F, AND LBS. ARE

	CONDUCTIVITY	DENSITY	HEAT CAPACITY
SAND	0.2	99	0.21
STEEL			
SOLID	18.0	489	0.18
MUSHY	15.0	489	1.57
LIQUID	10.0	489	0.21

(C) TIME STEP

THIS RELATION MAY GUIDE SELECTION OF A TIME STEP

TIME STEP=(DELTA X)**2/(4*ALPHA)

WHERE DELTA X IS THE NODE SPACING IN A REGION OF LARGE THERMAL GRADIENT AND ALPHA =CONDUCTIVITY/(HEAT CAPACITY*DENSITY) = THERMAL DIFFUSIVITY IN A REGION OF HIGH THERMAL GRADIENT, USUALLY SAND.

****

2. CREATE AN INPUT FILE -- AGRID

THE COMMENTS IN THIS SECTION REFER TO THE USE OF AGRID TO CREATE A GEOMETRIC MODEL AND FEM MESH. FIRST SOME HELPFUL DEFINITIONS.

MESH-FINITE ELEMENT SUBDIVISION OF THE GEOMETRIC MODEL OF THE MOLD AND CASTING
BRICK ELEMENT-HEXAHEDRAL ELEMENT CONTAINING 8 NODES AND SIX SIDES
ROWS-HORIZONTAL LINES THAT HAVE CONSTANT Z VALUES
COLUMNS- VERTICAL LINES THAT HAVE CONSTANT Y VALUES
PLANES-LINES THAT HAVE CONSTANT X VALUES.

THE MESH IS DRAWN BY DECIDING HOW MANY ROWS, COLUMNS, AND PLANES ARE TO BE USED TO SUBDIVIDE THE MODEL. IN PREPARATION THE LOCATION OF ROWS COLUMNS AND PLANES SHOULD BE NOTED.

THE ENTIRE INPUT FILE MAY BE CREATED BY EXECUTING AGRID AT A TIMESHARING TERMINAL. AGRID IS A SELF EXPLANATORY, INTERACTIVE PROGRAM. TO EXECUTE AGRID ON A TELETYPE OR GRAPHICS TERMINAL, TYPE

```
.EX  AGRID.FOR
```

****

3. RUN SIMULATION PROGRAM -- CSSP

THE SIMULATION CAN BE RUN EITHER ON TIMESHARING OR BATCH. THE MAXIMUM NUMBER OF NODES ON THE TIME-SHARING VERSION IS 100. FOR MORE THAN 100 NODES THE BATCH VERSION MUST BE USED.

(A) TIMESHARING EXECUTION (NODES $\leq$ 100)

THE FOLLOWING COMMANDS WILL EXECUTE THE SIMULATION AND HAVE THE TEMPERATURE AT EACH NODE PRINTED AT THE TERMINAL AFTER EVERY TEN TIMESTEPS.

```
.COPY MSH.CDR=XXXXX.DAT
.ASSIGN CDR: 1
.SET CDR MSH
.EXECUTE WHZBCK.FOR
```

WHERE XXXXX.DAT IS THE INPUT FILE CREATED BY AGRID AND WHZBCK.FOR IS THE TIMESHARING VERSION OF CSSP.

(B) BATCH EXECUTION

BATCH SIMULATION CAN BE QUEUED BY THE COMMAND

```
.OPRSTK SIM.CTL
```

WHERE SIM.CTL IS A CONTROL FILE THAT MOUNTS THE PROPER TAPE, MANAGES THE FILE, EXECUTES THE SIMULATION, AND PUTS THE OUTPUT ON TAPE. AN EXAMPLE OF A CONTROL FILE FOLLOWS:

```
$JOB NAME[*,*]/CORE:125K/TIME:00:59:00/OUTPUT:0/PRIOR:0
$DRIVES MT9
.MOUNT MT9:UARC/WE/VID:B14730/SL
.UARC
*THAW CSSP.FOR, XXXXX.DAT
*%FIN:
.COPY MESH2.DAT=XXXXX.DAT
.EXECUTE CSSP.FOR
.COPY YYYYY.DAT=TEMP.DAT
.R UARC
*FREEZE YYYYY.DAT
*%FIN:
.DELETE CSSP.*,XXXXX.DAT,YYYYY.DAT,STEMP.DAT,MESH2.DAT
$DATA
$EOD
$EOJ
```

WHERE XXXXX.DAT IS THE INPUT FILE CREATED BY AGRID AND YYYYY.DAT IS THE THE OUTPUT FILE CONTAINING NODAL TEMPERATURES AT SUCCESSIVE TIME STEPS.

****

4. PROCESS OUTPUT DATA

THESE INTERACTIVE TIMESHARING PROGRAMS CAN BE USED TO PRODUCE CALCOMP PLOTS. THEY REQUIRE A MESH FILE AND TEMPATURE FILE (SUCH AS XXXXX.DAT AS CREATED BY AGRID AND YYYYY.DAT FROM CSSP) OF A SIMULATION TO BE ON DISC STORAGE.

S.FOR	TEMPERATURE VS. TIME
TEMPOS.FOR	TEMPERATURE VS. POSITION
RATES.FOR	DTEMP/DTIME VS. TIME (COOLING RATES)
GRAD.FOR	DTEMP/DX VS. POSITION (THERMAL GRADIENTS)
MAP.FOR	TEMPERTURE PROFILE MAPS

****

FOR MORE DETAILED INFORMATION ON CSSP AND AGRID SEE:

H. BRODY ET AL, "IMPROVED FOUNDRY CASTINGS UTILIZING CAD/CAM," U. S. ARMY TACOM REPORT NO. 12574, OCTOBER 1981. SEE ESPECIALLY EXHIBIT B.

****

APPENDIX B

TESTS OF THE VALIDITY OF CSSP

APPENDIX B: TEST OF THE VALIDITY OF CSSP

Before CSSP was applied to the test casting, the program was tested on five example problems. Looking at these problems enables one to determine whether CSSP can handle relatively simple problems and build confidence in its use. These examples considerd such phenomena as convection, conduction, solidification, boundary conditions, and transient response. Where possible, the numerical solutions were compared to analytical solutions.

E2-B-1 Isothermal Case

A steel rod, initially at 100^{o}F is placed in air at 100^{o}F with a convective heat transfer coefficient of 25 BTU/(ft^{2} ^{o}F hr). What is the change in temperature of the steel rod? The analytical solution, derived from basic heat transfer principles, is that there is no change in temperature of the steel rod. The results of the simulation in Figure 12 show that CSSP agrees with the analytical solution that there should be no change in temperature.

E2-B-2 Convective Cooling

A steel cube initially at 300^{o}F is suddenly immersed in a fluid at 100^{o}F with a convective heat transfer coefficient of 25 BTU/(ft^{2} ^{o}F hr), What is the transient temperature behavior of the rod? The relevant data are in Table E2-B-1. The analytical solution is one that can be found in any basic heat transfer textbook. If the Biot number of the cube is less than 0.1 then a solution for a problem of negligible internal resistance may be used. The equation for the Biot number Bi is

$$Bi = \frac{hr_o}{k} \qquad \text{(B-1)}$$

where h is the convective heat transfer coefficient, k is the thermal conductivity of the cube, and r is the characteristic length of the cube. For this problem

$$Bi = 0.0153 < 0.1 \qquad \text{(B-2)}$$

For a Biot number less than 0.1, the equation

$$\frac{T - T_\infty}{T_o - T_\infty} = \exp - \frac{hAt}{dC_pV} \qquad \text{(B-3)}$$

may be used. In the equation, T is the temperature of the cube, T_o is the initial temperature of the rod, T_∞ is the temperature of the fluid, h is the convective heat transfer coefficient, A is the surface area of the cube, t is the time, d is the density of the cube, C_p is the heat

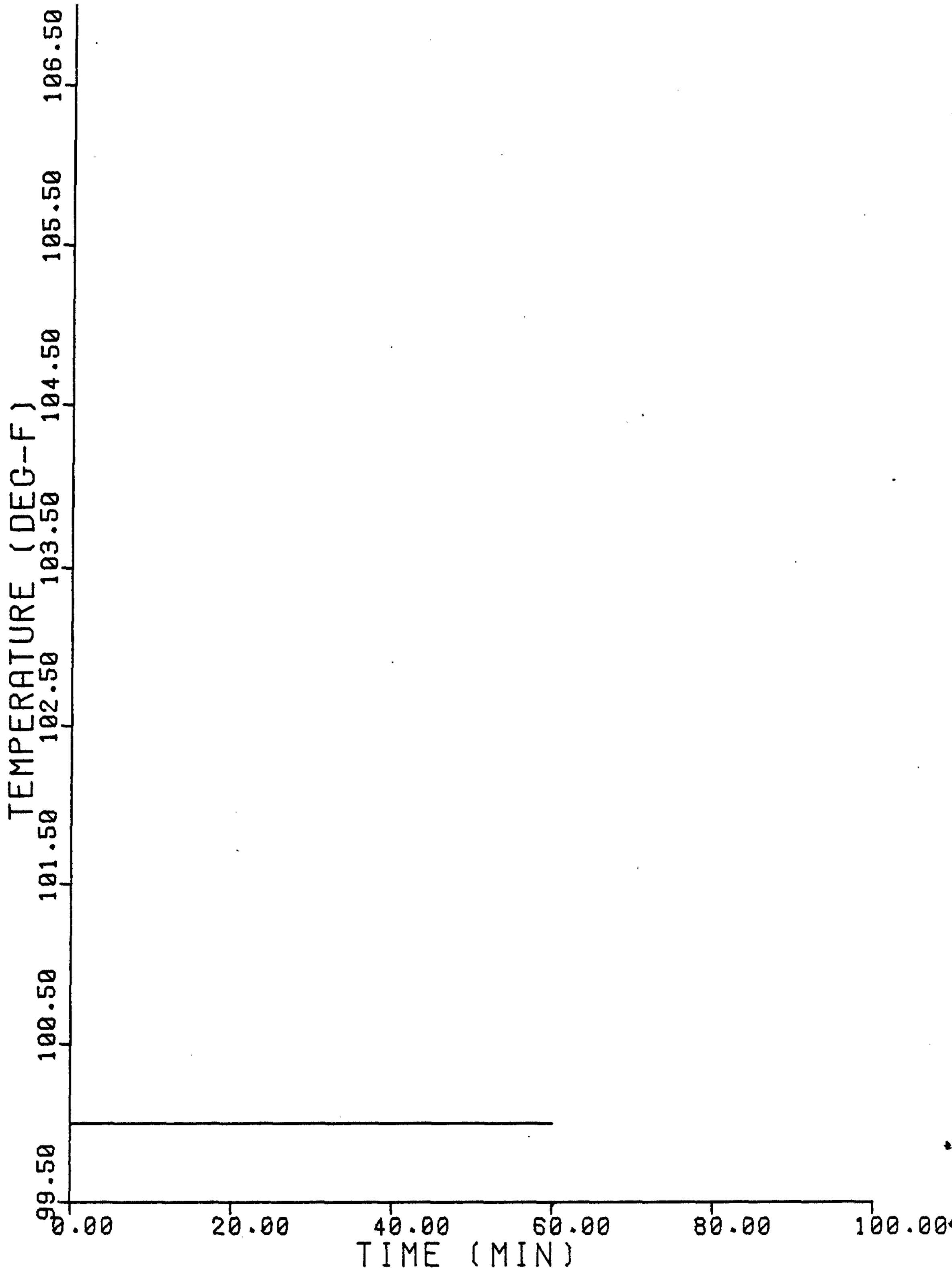


Figure E2-B-1: Isothermal simulation results.

TABLE E2-B-1

Data for Convective Cooling Problem

Material: Steel Rod

$\rho = 489.0\ lb/ft^3$	Length $= 0.0833$ ft
$k = 17.0\ BTU/hr\ ft^{o}F$	$r_o = 0.0208$ ft
$C_p = 0.157\ BTU/lb^{o}F$	Volume $= 0.0105\ ft^3$
$\alpha = 0.22\ ft^2/hr$	Area $= 1.0035\ ft^3$
$T_o = 300^{o}F$	$T_\infty = 100^{o}F$
$h = 25\ BTU/hr\ ft^2\ {}^{o}F$	

capacitance of the cube, and V is the volume of the cube. The numerical and analytical solutions are plotted in Figure E2-B-2 and the relative error between the two solutions shown in Figure E2-B-3. The close agreement between the two solutions can be seen in these two figures.

E2-B-3 Fixed End Temperature Response

This test problem is an insulated steel rod initially ($t < 0$) at $100^{\circ}F$. Then, for $t<0$ the left end is maintained at $100^{\circ}F$ and the right end is maintained at $150^{\circ}F$. What is the transient temperature response of the bar at various points along the axis?

The heat flow equation for this problem is

$$\frac{\partial^2 T}{\partial X^2} = \frac{1}{\alpha^2} \frac{\partial T}{\partial t} \tag{B-4}$$

The initial condition is

$$T(X,0) = 100^{\circ}F \tag{B-5}$$

The boundary conditions are

$$T(0,t) = 100^{\circ}F \tag{B-6}$$

$$T(6,t) = 150^{\circ}F \tag{B-7}$$

The solution of the heat equation with these constraints uses techniques in solving partial differential equations. Hence, the solution is

$$T(X,t) = 100 + \frac{50X}{6} + \sum_{n=1}^{\infty} a_n \sin\left(\frac{n\pi X}{6}\right) \exp - \left[\left(\frac{n\pi\alpha}{6}\right)^2 t\right] \tag{B-8}$$

Where

$$a_n = \frac{2}{6} \int_0^6 100 \sin\left(\frac{n\pi X}{6}\right)dx + \frac{2}{n\pi} (150 \cos n\pi - 100) \tag{B-9}$$

The finite element numerical solution requires one to subdivide the bar into nodes and elements. The scheme involving eightyfour nodes and twenty elements is pictured in Figure E2-B-4. The numerical and analytical solution show close agreement in Figures E2-B-5 to E2-B-7.

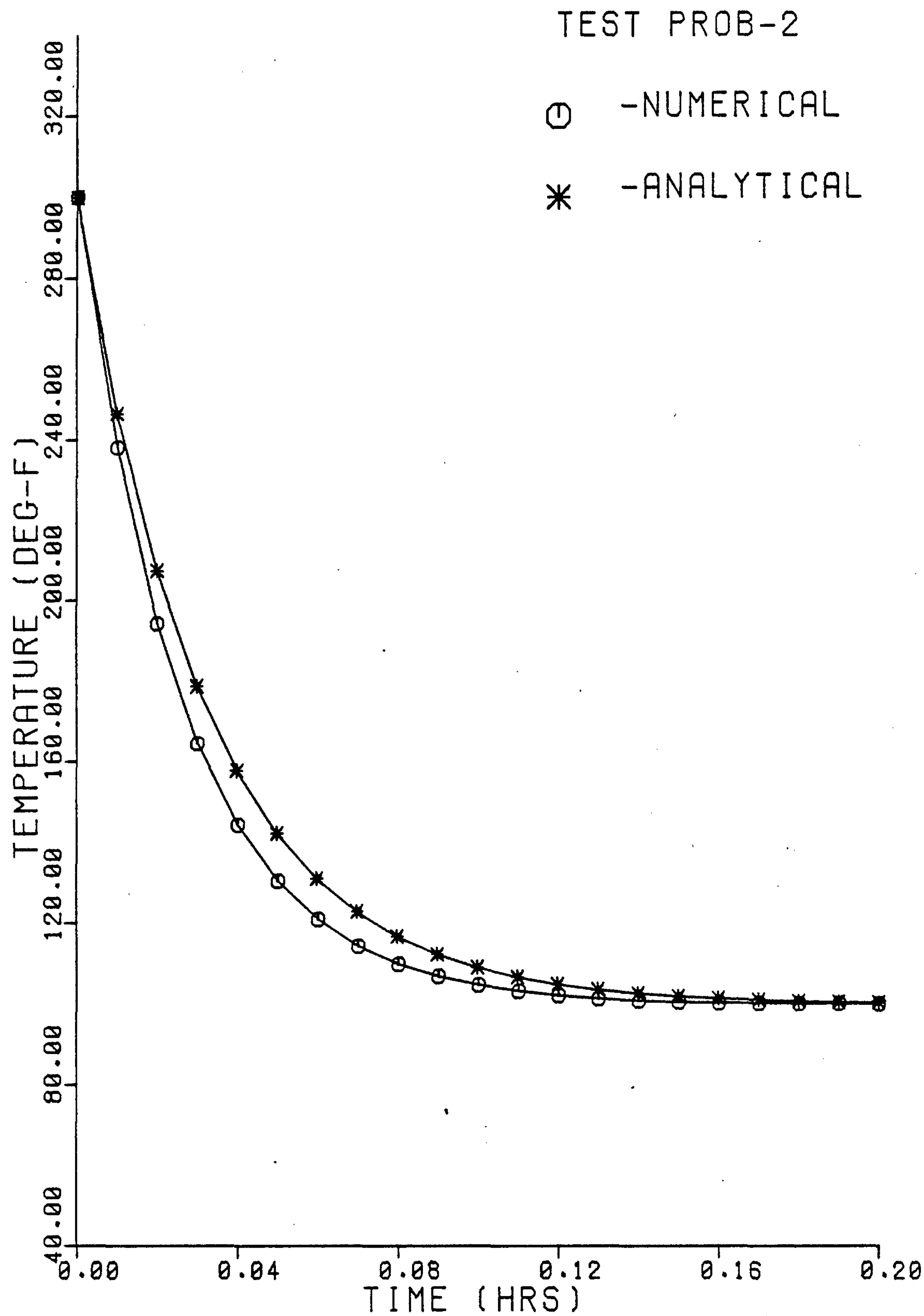


Figure E2-B-2: Convective cooling simulation results.

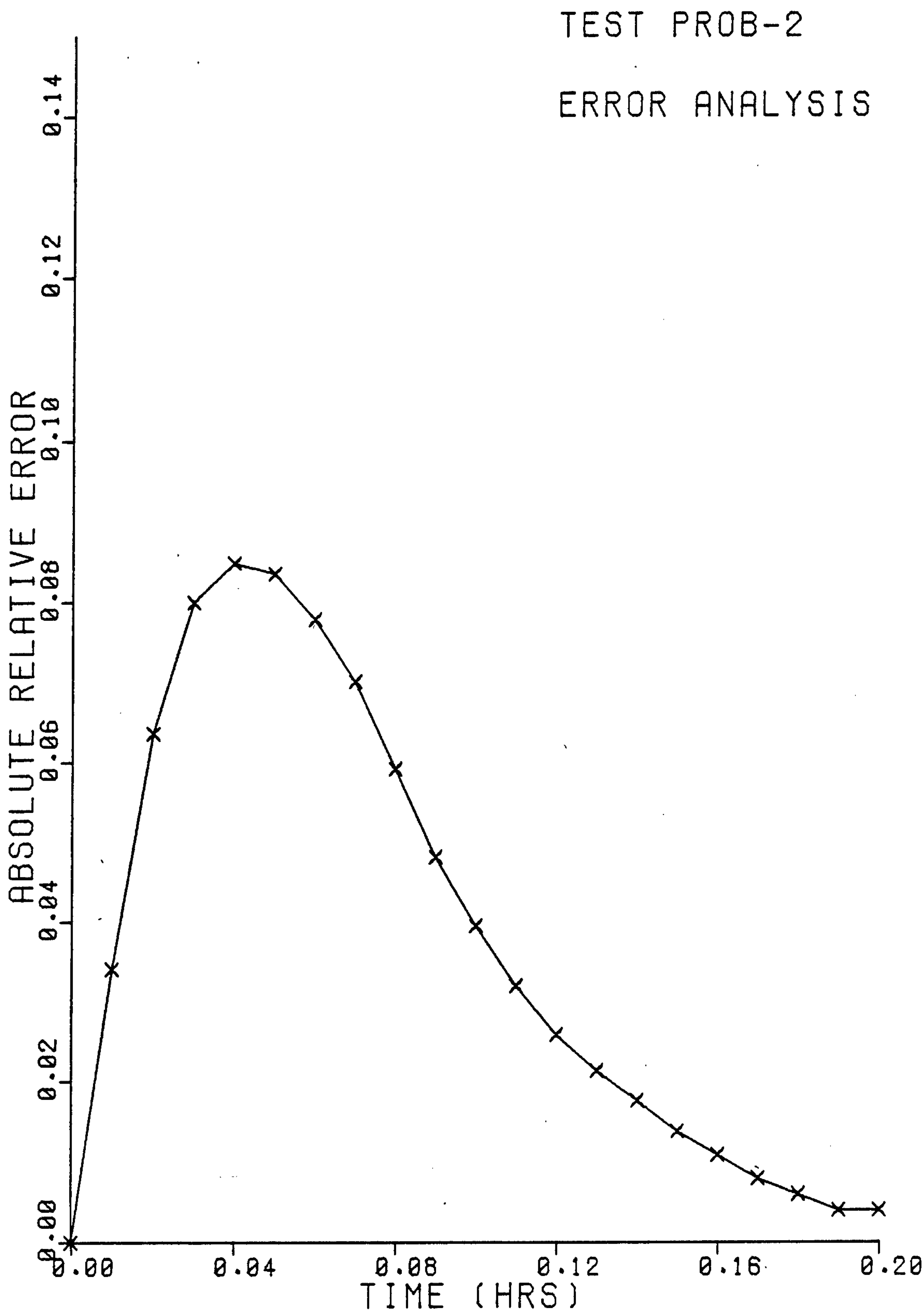


Figure E2-B-3: Relative error for convective cooling simulation.

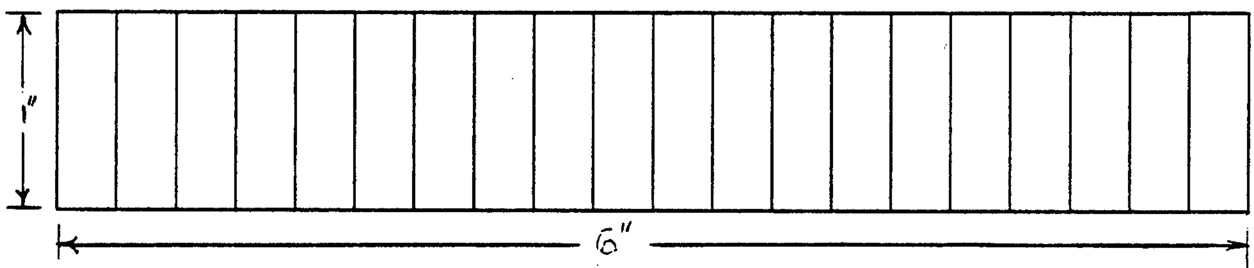


Figure E2-B-4: Mesh for fixed end temperature problem.

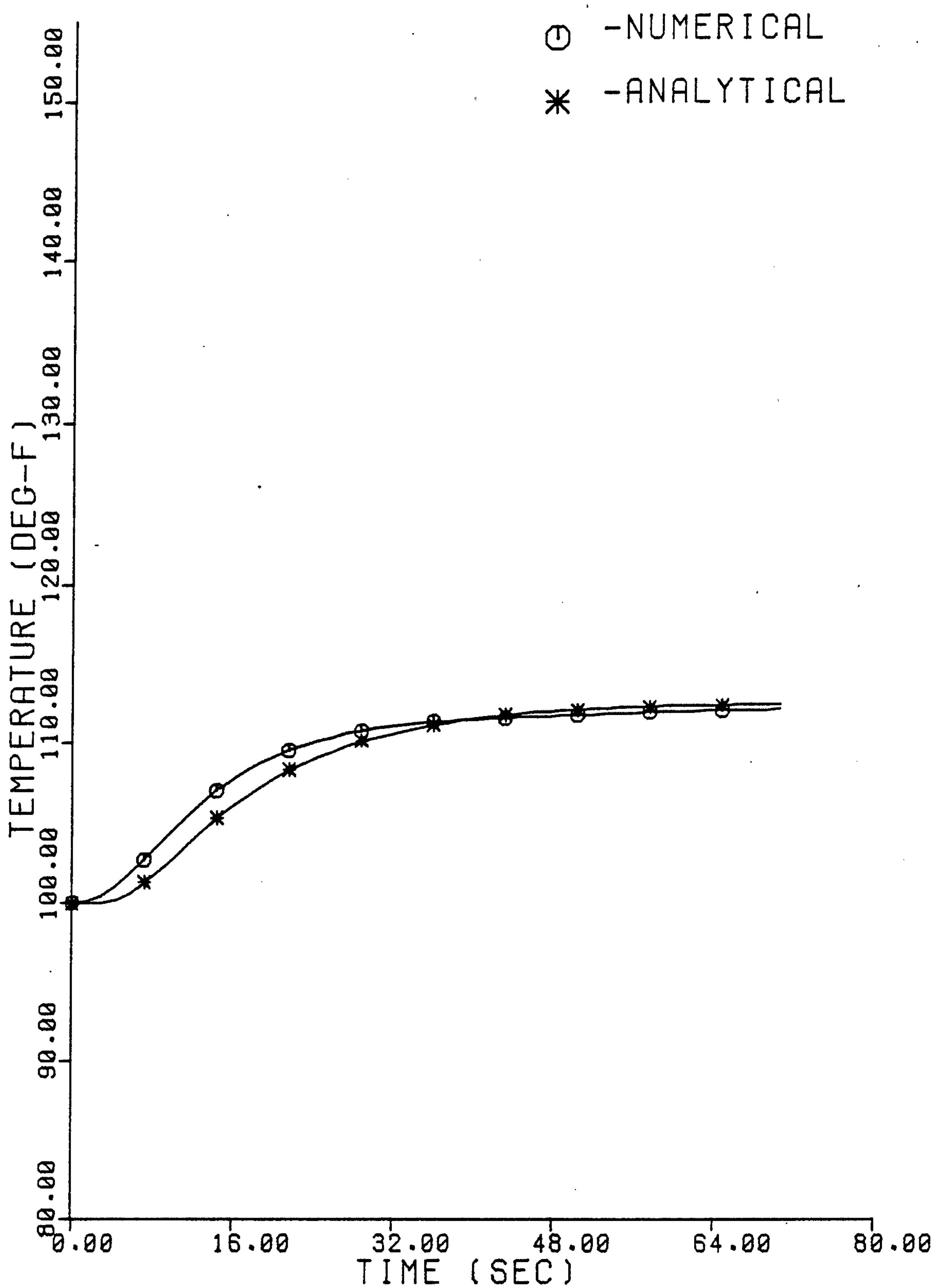


Figure E2-B-5: Fixed end temperature response results at X = 1.5 inches.

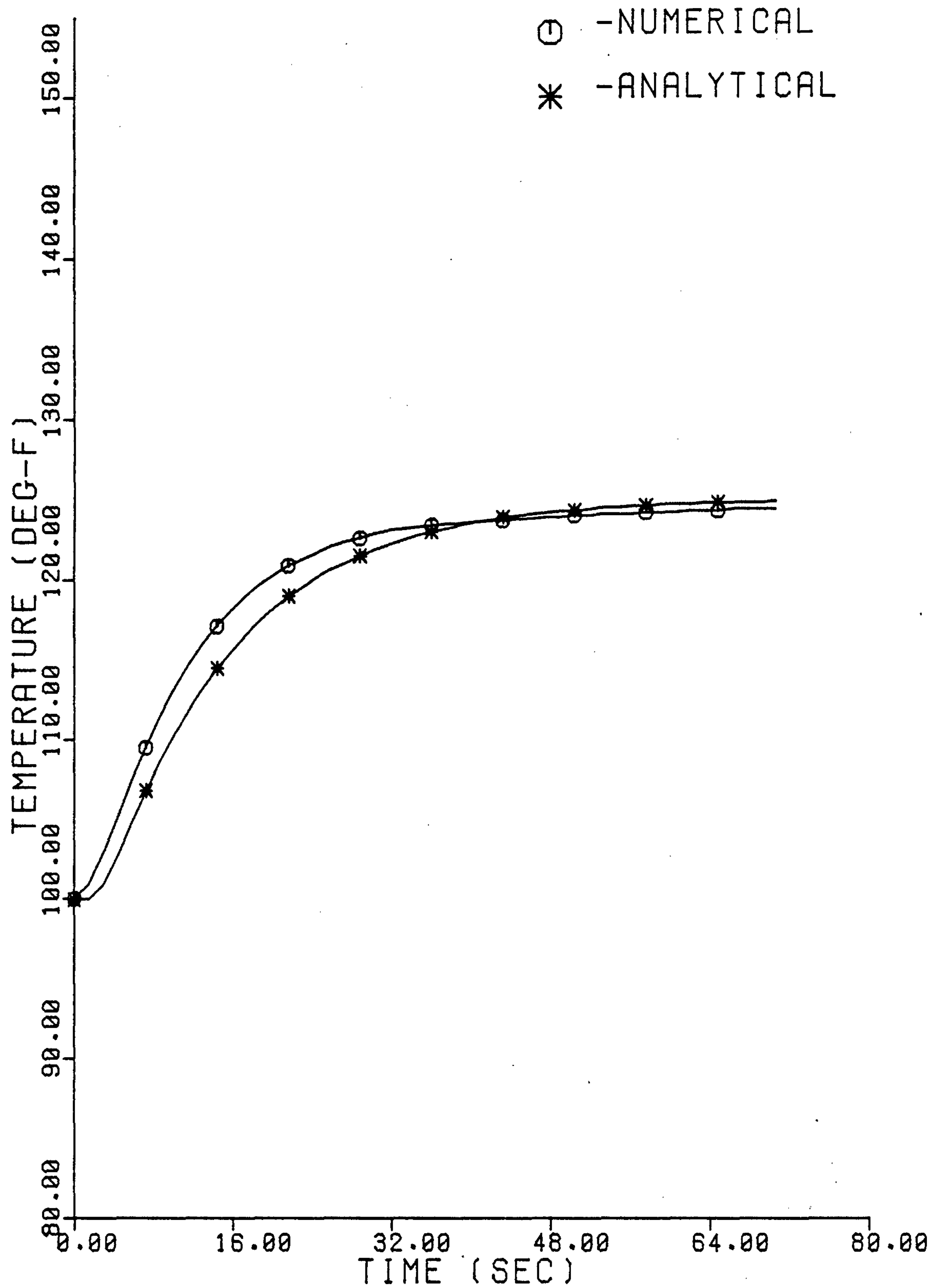


Figure E2-B-6: Fixed end temperature response results at X = 3.0 inches.

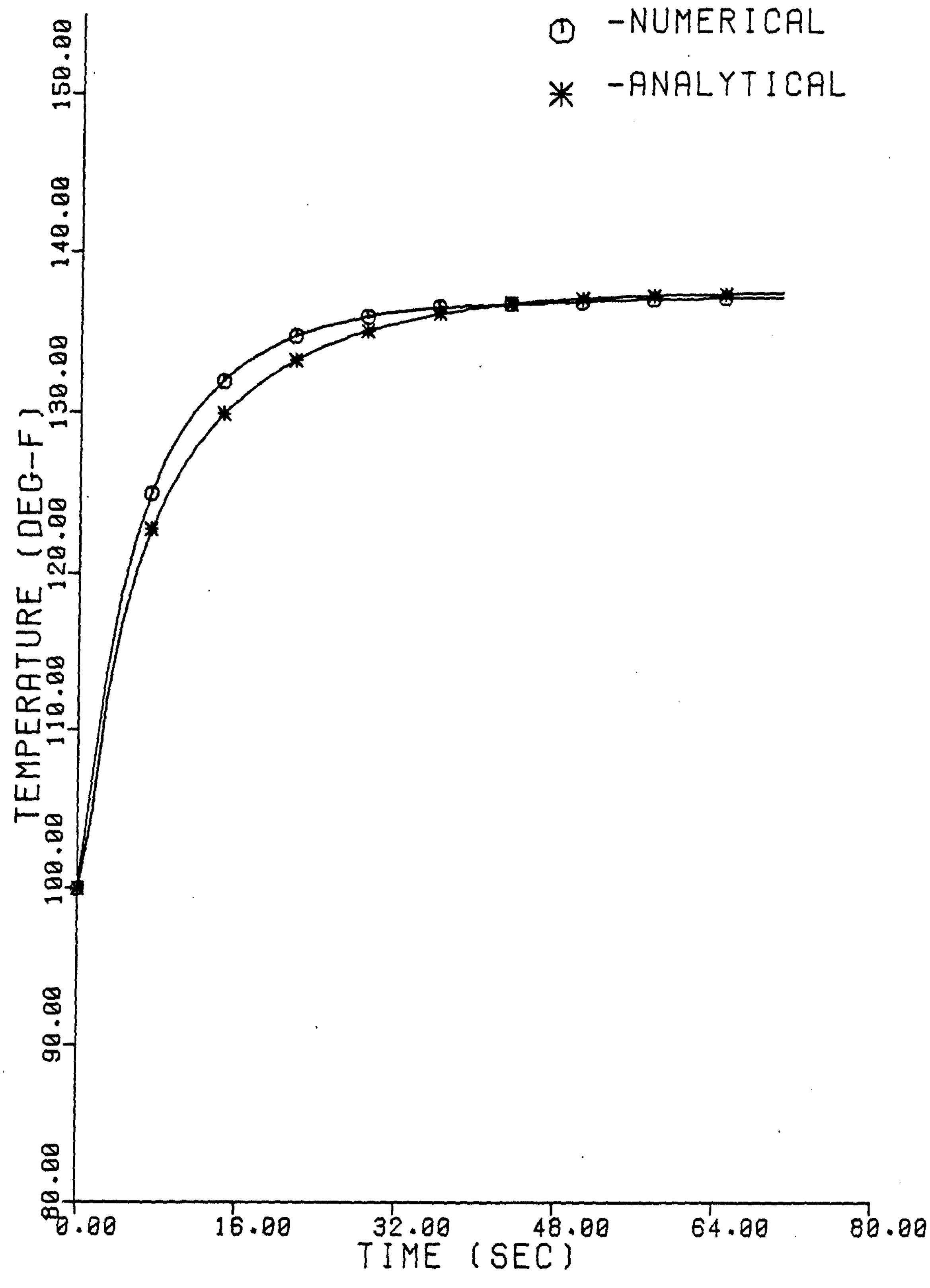


Figure E2-B-7: Fixed end temperature response results at X = 4.5 inches.

E2-B-4 Solidification of a Steel Rod

Test problem 4 is designed to study the solidification of an insulated steel rod with an initial temperature distribution that is linear from 2,600°F to 2,900°F. What will be the steadystate temperature of the rod?

Since, the bar is insulated there will be heat loss. Thus, the concept of conservation of energy can be applied to the volume of the rod. The bar is first divided into six sections lettered A through F as shown in Figure E2-B-8. The initial average temperatures of the sections are

$$T_A = 2{,}625^{\circ}F \tag{B-10}$$

$$T_B = 2{,}675^{\circ}F \tag{B-11}$$

$$T_C = 2{,}725^{\circ}F \tag{B-12}$$

$$T_D = 2{,}775^{\circ}F \tag{B-13}$$

$$T_E = 2{,}825^{\circ}F \tag{B-14}$$

$$T_F = 2{,}875^{\circ}F \tag{B-15}$$

These sections will be assumed to approach a final steady state temperature T. Some sections will increase in temperature and others will decrease in temperature. Therefore, the energy gained by some sections must be offset by an energy loss in other sections The computation of the steady-state temperature is determined as follows.

1. Assume T will be between any two section temperatures.
2. Assume all sections have the same mass.
3. Write the expression for the energy gained or lost for each section.
4. Sum equations.
5. Solve for 5.

A table of heat capacitances used in the solution is in Table E2-B-2.

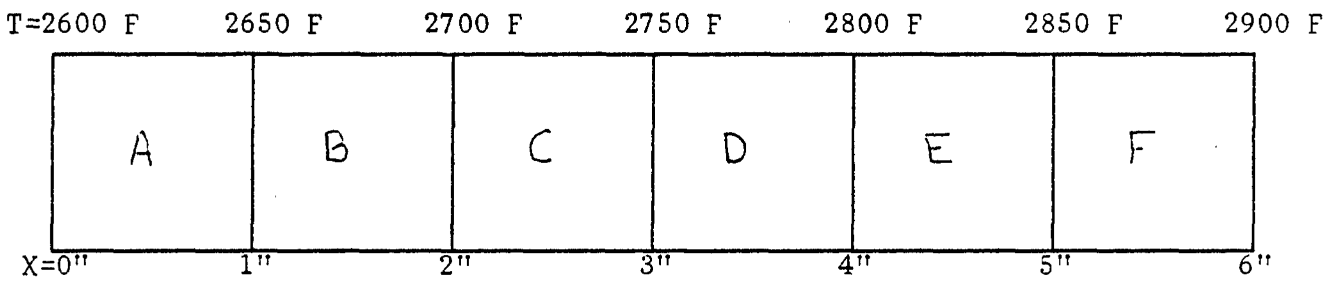


Figure E2-B-8: Solidifying steel rod model.

TABLE E2-B-2

Heat Capacitances Used for Solidifying Steel Rod Problem

Range (^oF)	Heat Capacitance (BTU/lb ^oF)	Symbol
$T_i < 2643$	0.15742	CPS
$2643 < T_i < 2735$	1.14595	CPM
$T_i < 2735$	0.17899	CPL

Solution:

$$\text{Assume } 2675 < T < 2725 \tag{B-16}$$

$$\text{Section A} \quad \Delta E_A = (2643-T_A)CPS - (T-2643)CPM \tag{B-17}$$

$$\text{Section B} \quad \Delta E_B = (T-T_B)CPM \tag{B-18}$$

$$\text{Section C} \quad \Delta E_C = (T-T_C)CPM \tag{B-19}$$

$$\text{Section D} \quad \Delta E_D = (2735-T_D)CPL - (T-2735)CPM \tag{B-20}$$

$$\text{Section E} \quad \Delta E_E = (2735-T_E)CPL - (T-2735)CPM \tag{B-21}$$

$$\text{Section F} \quad \Delta E_F = (2735-T_F)CPL - (T-2735)CPM \tag{B-22}$$

Using the conservation of energy equation, one gets

$$\Delta E_A + \Delta E_B + \Delta E_C + \Delta E_D + \Delta E_E + \Delta E_F = 0 \tag{B-23}$$

Then, solving this equation for T yields

$$T = 2715^{o}F \tag{B-24}$$

The finite element solution was computed with a mesh containing twentyeight nodes and six hexahedral elements. This numerical solution, pictured in Figure E2-B-9 arrives at the calculated steady-state temperature. However, the transient accuracy of the numerical solution is unknown at this time.

E2-B-5 Large Initial Gradient

An insulated steel rod is analysed in this problem. Initially, half of the rod is at 2,600^{o}F and half of the rod is at 1,300^{o}F. Logically, since there are constant thermal properties in this temperature range, the final temperature will be the average of the two initial temperatures. Thus, the analytical solution requires the steady-state temperature to be 1,950^{o}F. Using a mesh containing twenty-eight nodes and six hexahedral nodes, CSSP exhibits the cooling in Figure E2-B-10 which agree with the analytical solution. Although there is a large initial temperature gradient, CSSP still works well.

E2-B-6 Summary of Test Problems

The important parameters and results of the test problems are presented in Tables E2-B-3 to E2-B-7.

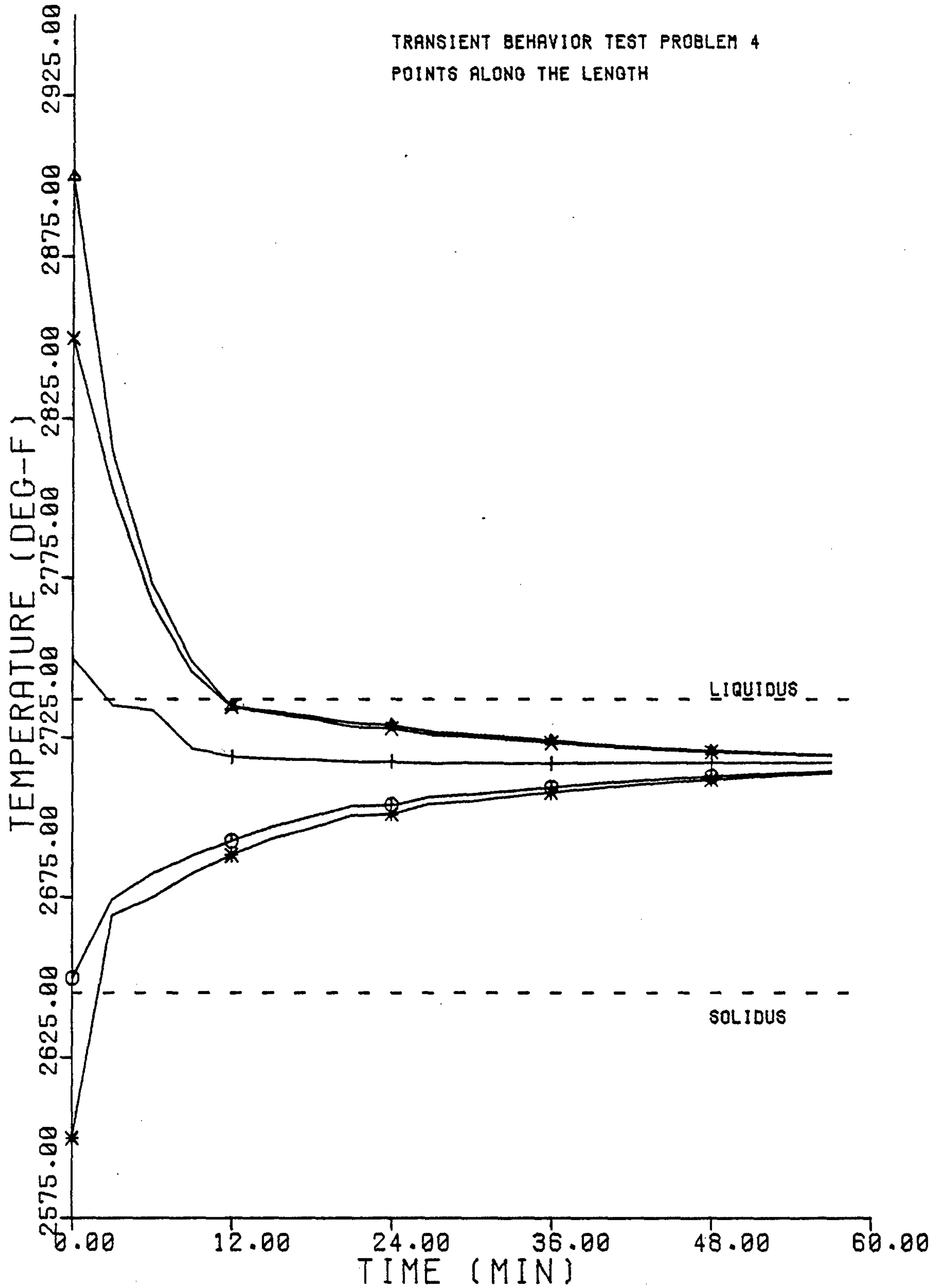


Figure E2-B-9: Numerical solution for solidifying steel rod.

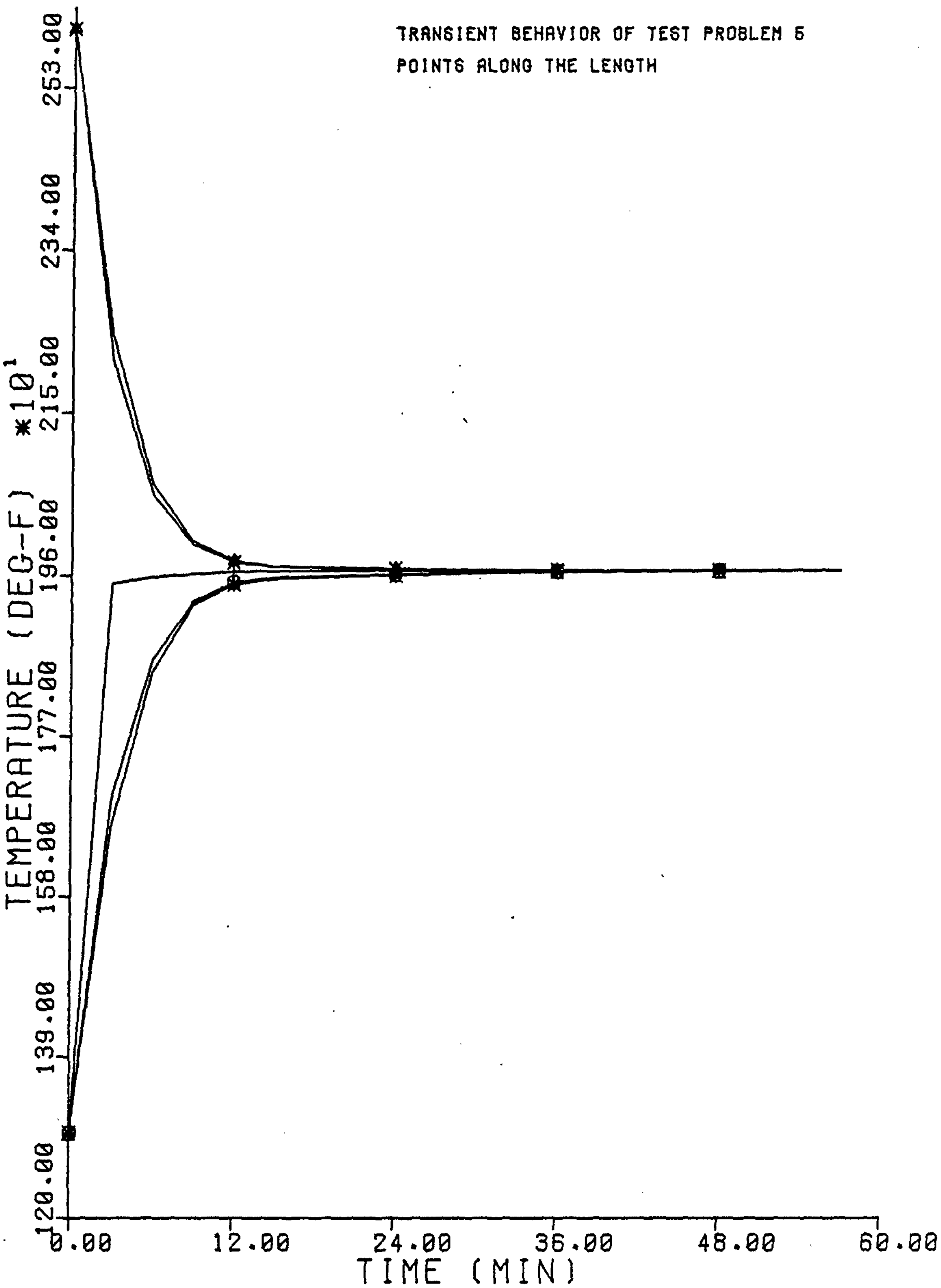


Figure E2-B-10: Numerical solution for large initial gradient problem.

TABLE E2-B-3

Summary of Test Problem 1

Material:	Steel Rod
Initial Condition:	Uniform Temperature
	$T_o = 100$ F
Enviornment:	Fluid
	$T_\infty = 100$ F
Important Parameter:	$h = 25 \dfrac{\text{BTU}}{\text{ft}^2 \text{ F hr}}$
Results:	Numerical and Analytical Solutions Agree

TABLE E2-B-4

Summary of Test Problem 2

Material:	Steel Rod
Initial Condition:	Uniform Temperature $T_o = 100$ F
Environment:	Fluid T = 100 F
Important Parameter:	$h = 25 \frac{BTU}{ft^2 \, F \, hr}$
Results:	Close Agreement Between Numerical and Analytical Solutions

TABLE E2-B-5

Summary of Test Problem 3

Material:	Steel Rod
Initial Condition:	Uniform Temperature $T_o = 100$ F
Boundary Conditions:	$T(0,t) = 100$ F $T(6,t) = 150$ F
Environment:	Insulated
Results:	Close Agreement Between Numerical and Analytical Solutions

TABLE E2-B-6

Summary of Test Problem 4

Material:	Steel Rod Undergoing Solidification
Initial Condition:	Linear Temperature Distribution $T(x) = 2600 + 300\ (X/L)$
Environment:	Insulated
Important Parameters:	$TSOL = 2643\ F \qquad CPS = 0.15742\ \frac{BTU}{lb\ ^{o}F}$ $TLIQ = 2735\ ^{o}F \qquad CPM = 1.14595\ \frac{BTU}{lb\ ^{o}F}$ $CPL = 0.17899\ \frac{BTU}{lb\ ^{o}F}$
Results:	Numerical and Analytical Solutions Agree

TABLE E2-B-7

Summary of Test Problem 5

Material	Steel Rod
Initial Condition:	left half at 2600 F right half at 1300 F
Environment:	Insulated
Resutls:	Numerical and Analytical Solutions Agree

EXHIBIT 3

FILLING RATE AND HEAT LOSS ANALYSIS FOR CASTING GATING SYSTEMS

DOCUMENTATION

PHASE I

TABLE OF CONTENTS

LIST OF TABLES

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FLUID FLOW ANALYSIS

E3-1 GENERAL

E3-1-1 Filling Rate Problem

The production of quality castings requires proper attention to the detailed design of the gating system, in particular the sprues, runners and ingates. It has been seen that riser design is a function of the solidification time for the casting. Similarly the design of the running and gating system is a function of the required filling time; that is, of the filling rate.

A computer program, based on the Bernoulli energy equation, was developed to calculate the velocity of the molten metal at the ingate and the time required to fill the casting cavity for different kinds of gating systems with or without pressure acting at the ingate due to filling of the mold cavity.

The technical basis of the analysis is described in Section E3-2-1. An example of program use is given in Section E3-3. To properly use the program it is necessary to read the technical background section.

E3-1-2 Heat Loss in the Gating System

When molten metal is poured into a mold through a runner that is initially unheated, heat is transferred from the metal to the runner. As a result, the metal arrives at the mold at a lower temperature than the temperature at which it was poured.

E. W. Jones, et al.* simulated the heat transfer problem for the case of a sand runner by means of an electrical analog. A computer program was developed to calculate the temperature loss in the gating system based on their work and the pouring rate program developed earlier by the author.

*E. W. Jones, W. H. Steigelmann, and G. P. Wachtell, "Heat Transfer from Molten Metal to Sand Mold Runners", AFS Transactions, 71, 1963, pp. 817-825.

The technical basis of the calculation is described in Section E3-2-2. An example of the use of the program is given in Section E3-3. The filling rate calculation and the heat loss calculation are combined in the same program. It is necessary to first calculate the flow velocity in the gating system before heat loss can be calculated.

E3-2 DEVELOPMENT OF THE MODEL

E3-2-1 Filling Rate Solutions

This model is built to predict the filling rate of the molten metal at the ingate for different kinds of gating systems. The basic equation used is the Bernoulli energy balance*:

$$\int_{P_1}^{P_2} \frac{dP}{d} + \left[\frac{\bar{V}_2^{\,2}}{2B_2} - \frac{\bar{V}_1^{\,2}}{2B_1}\right] + g\Delta z + M^* + E_f = 0 \tag{2-1}$$

where P = Pressure, lbs force/ square ft

d = Density, lbs. mass/ cubic ft.

V = Average velocity across the cross-sectional area, ft/sec

$$\frac{1}{B} = \frac{1}{A}\int_0^A \left(\frac{v}{\bar{v}}\right)^3 dA$$

where v is the velocity profile across the cross-sectional area.

g = The acceleration of gravity, ft/(square sec)

Z = Difference in potential head, ft

M*= Mechanical energy, (square ft)/(square sec)

E_f= Frictional energy loss, (square ft)/(square sec)

This model is considered as an iterative way to compute the velocity of the molten metal at the ingate; that is the flow rate. In sand mold casting, the mold material is porous, and the pressure is essentially atmospheric. Therefore, the pressure term can be eliminated. For laminar flow in a circular tube, B=0.5, and for turbulent flow, B is nearly unity. Since flow in gating system is generally turbulent, a value of 1.0 has been used for B.

The first assumption in developing this Bernoulli's model is that the molten metal level in the basin is constant. A typical gating system is shown in Figure E3-1. Also, it is assumed no external mechanical energy source is supplied; flow is driven by gravity only. The second assumption,

*G. H. Geiger and D. R. Poirier, Transport Phenomena in Metallurgy, Addison-Wesley (New York, 1973).

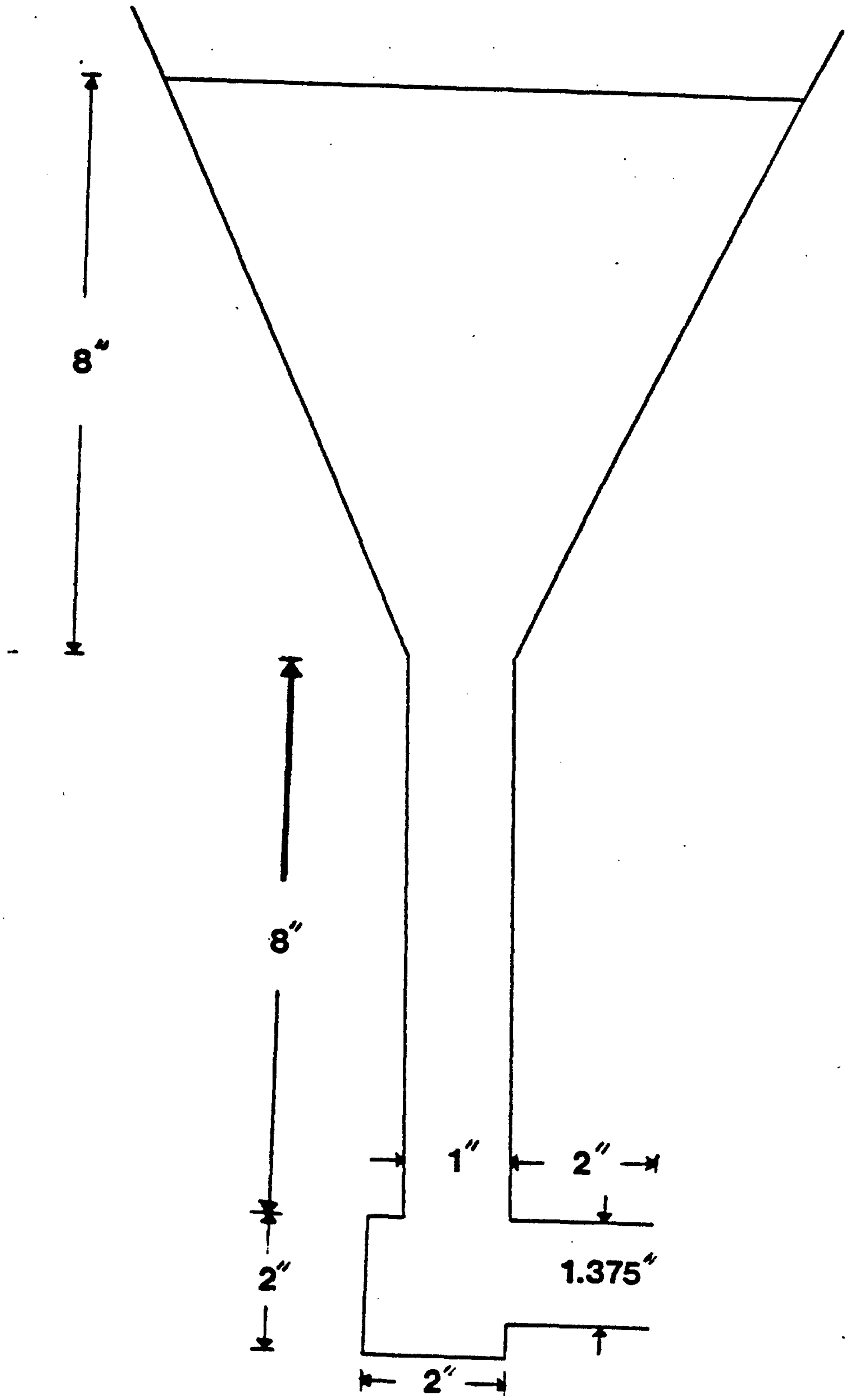

Figure E3-1: Geometry of a gating system

which is also the most important assumption in this model, is that the fluid flow in the gating system is well developed.

The most crucial part in this model is to estimate the term of frictional energy loss. It consists of the following parts:

(a) Friction losses in straight conduits:

In straight conduits, the frictional energy loss E_f is due directly to the viscous shear force within the molten metal and between the molten metal and the mold walls. E_f may be evaluated with the well-known Fanning equation

$$E_f = 2f\ (L/D)\ \overline{V}^2 \qquad (2\text{-}2)$$

where f is the friction factor, L and D are the length and diameter of the conduit. The friction factor, f, can be found by using Moody's Diagram*, see Figure E3-2. But in a computer model like this, a mathematical equation has to be used instead of the diagram. An empirical formula which was proposed by Moody** is used:

$$f = 0.0014\ [1+(20{,}000(\varepsilon/D) + 10^6\ N_R^{-1})^{1/3}] \qquad (2\text{-}3)$$

where ε is the absolute roughness of the mold materials and ε/D is referred to as relative roughness, see Table E3-1. In this analysis, a default value of ε =0.012 inch has been selected as an approximation for a sand mold. N_R is the Reynold Number of the flow. This formula is applicable over the usual range of engineering problems for values of N_R from 4,000 to 10^7, and for values of ε/D up to 0.01.

One thing should be noticed here, the evaluation of Reynolds Number requires velocity of the fluid, which is a variable to be found. Therefore, an iterative, trial and error process is employed by the program.

(b) Friction losses for fluid flow through valves and fittings:

*L. F. Moody, "Friction Factor for Pipe Flow", Trans. ASME, 66, 1944, pp. 671-684.

**L. F. Moody, "An Approximate Formula for Pipe Friction Factors, Mech. Engrng., 69, 1947, pp. 1005-1006.

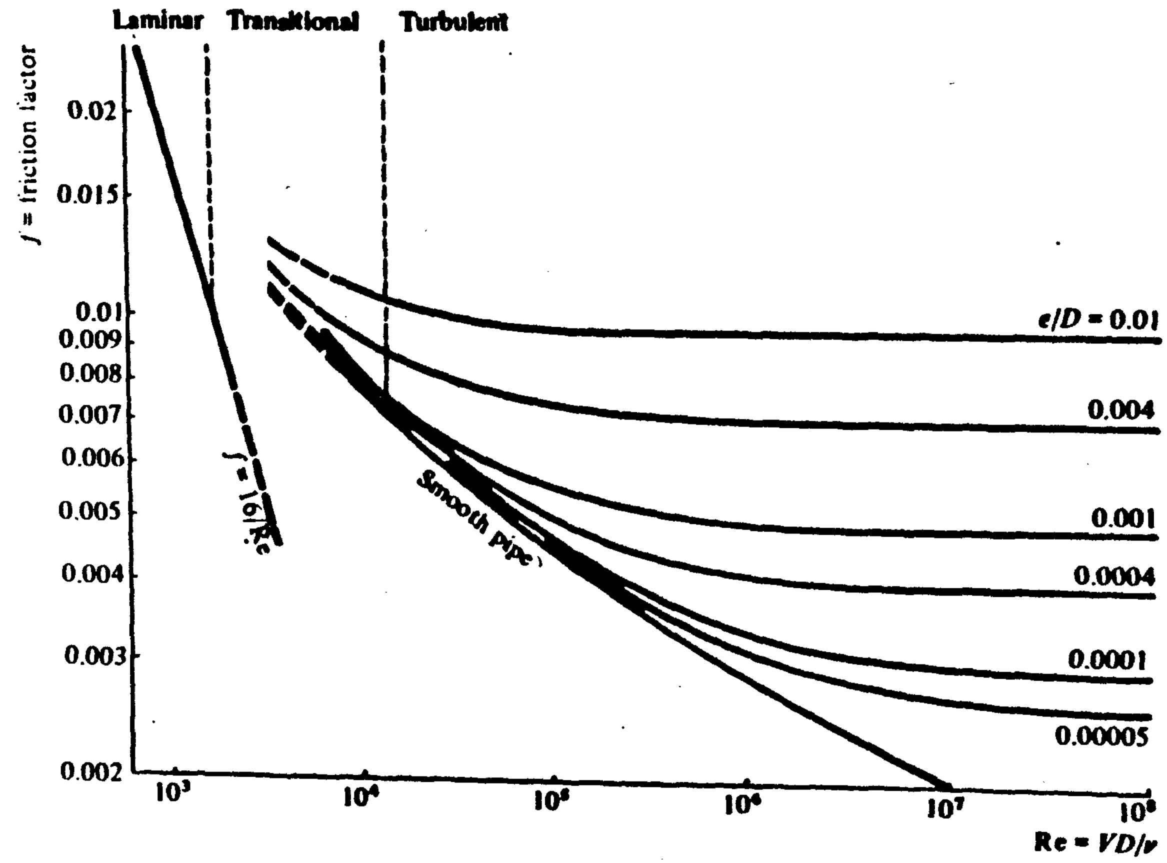

Figure E3-2: Friction factors for flow in tubes. (L. F. Moody, Mech. Engrng., 69, 1947, pp. 1005-1006.)

Table E3-1 Values of absolute roughness ε for new pipes*

	Ft.	In.
Drawn tubing, brass, lead, glass, centrifugally spun cement, bituminous lining, transit	0.000005	0.00006
Commercial steel or wrought iron....................	0.00015	0.0018
Welded-steel pipe..................................	0.00015	0.0018
Asphalt-dipped cast iron............................	0.004	0.0048
Galvanized iron....................................	0.0005	0.006
Cast iron, average..................................	0.00085	0.0102
Wood stave...	0.006 to 0.003	0.0072 to 0.036
Concrete...	0.001 to 0.01	0.012 to 0.12
Riveted steel.......................................	0.003 to 0.03	0.036 to 0.36

*L. F. Moody, "An Approximate Formula for Pipe Friction Factors", Mech. Engng., 69, 1947, pp. 1005-1006.

These energy losses are due to the changing direction of fluids and are usually handled by assigning an equivalent length/diameter ratio to the fixture such that the energy loss could be given by:

$$E = 2f(Le/D)\overline{V} \qquad (2\text{-}4)$$

The equivalent Le/D for turbulent flow of various fittings similar to the constructions normally employed in gating systems can be found in Table E3-2.*

(c) Friction losses due to changing cross-sectional area:

The friction losses for the particular geometry that upsets flow in conduits is evaluated in the following manner:

$$E = \tfrac{1}{2}\overline{V}^2 \; e_f \qquad (2\text{-}5)$$

where $\overline{V}$ is the velocity of fluid in the smaller cross-section. e_f corresponds to a friction factor with built-in geometry effects and is evaluated in different ways for different cases, see Figure E3-3.

(i) For sudden expansion:

The calculation of e_f (Figure E3-4) associated with sudden enlargement is given in Kay's paper** by:

$$e_f = 1 - 2K_{ds}\, S + S^2 \qquad (2\text{-}6)$$

where S is the expansion area ratio A_s / A_1, K_{ds} is the momentum velocity-distribution coefficient and can be given by:

$$K_{ds} = 1.09068\,(4f) + 0.05884\,(4f)^{1/2} + 1 \qquad (2\text{-}7)$$

*See previous page.
**W. M. Kays, "Loss Coefficient for Abrupt Changes in Flow Cross Section with Low Reynolds Number Flow in Single and Multiple-Tube System", Trans. ASME, 72, 1950, pp. 1067-1074.

Table E3-2 Equivalency length for various fixtures, turbulent flow

Fitting	Le/D	Fitting	Le/D
45 elbow	15	Tee (as el, entering branch)	90
90 elbow, standard radius	31	Coupling, unions	Negligible
90 elbow, medium radius	26	Tee (as el, entering run)	7
90 elbow, long sweep	20	180 close return bend	75
90 square elbow	65		

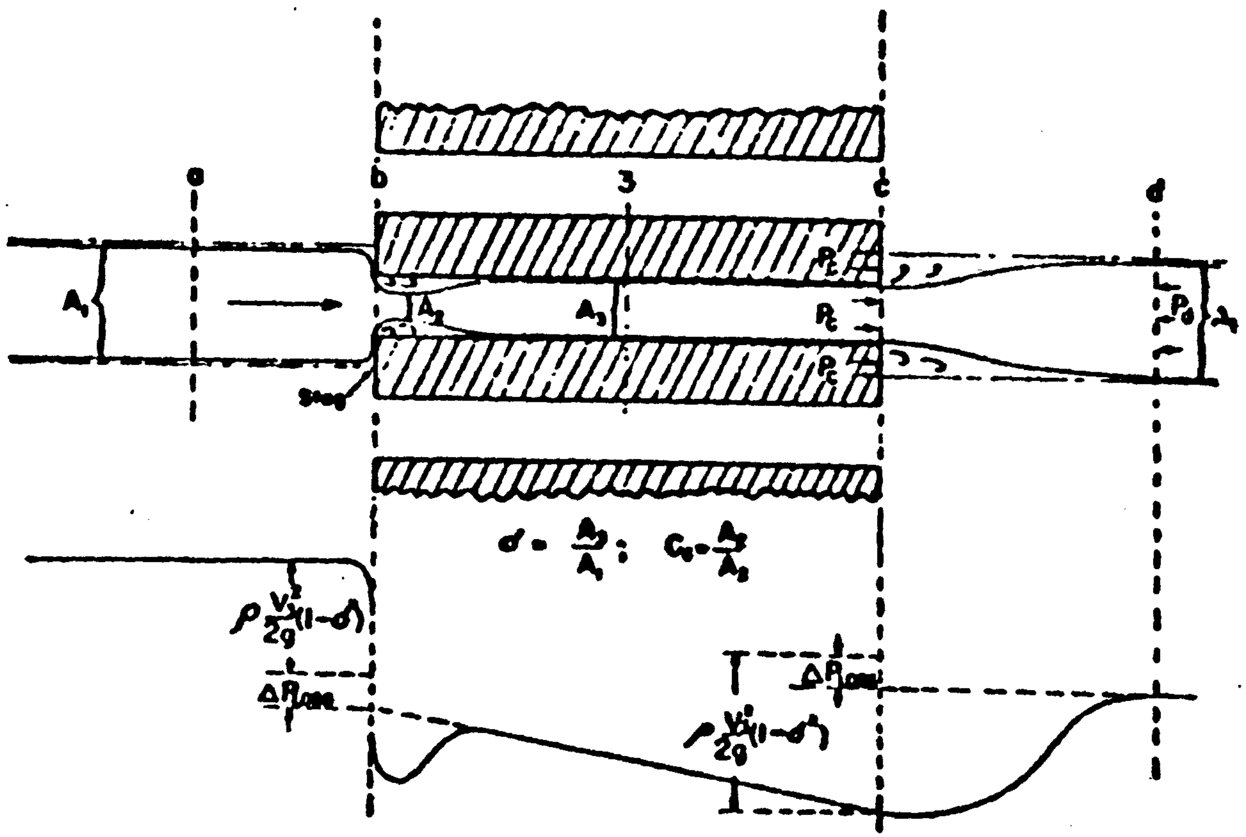

Figure E3-3: System diagram and pressure variation for abrupt contraction and expansion. (W. M. Kays, Trans. ASME, 72, 1950, pp. 1076-1074)

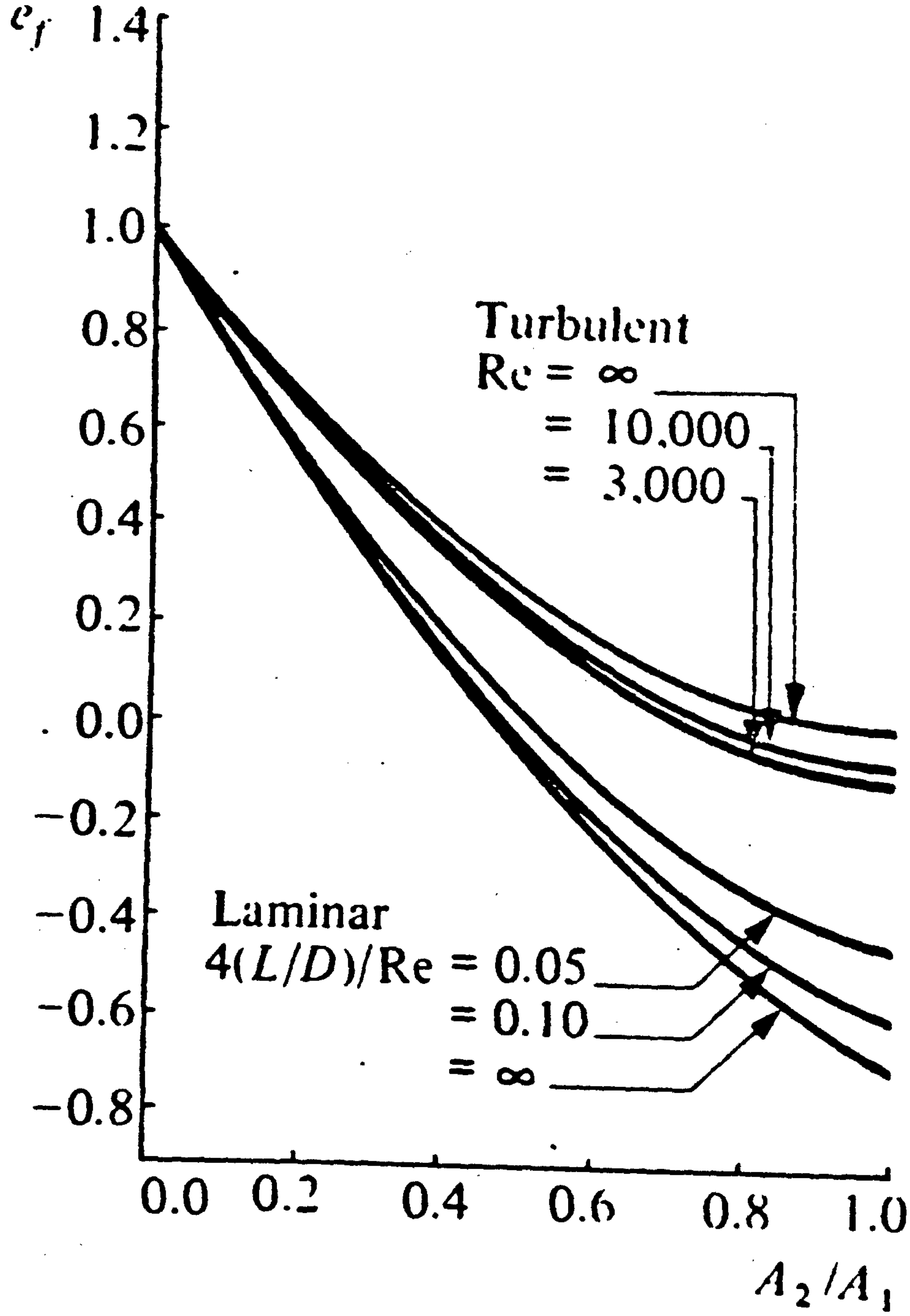

Figure E3-4: Friction-loss factor for sudden expansion

where f is the Fanning friction factor given by:

$$f = 0.049\,(N_R)^{-0.2} \tag{2-8}$$

This formula is applicable for the Reynolds Number ranging from 500 to 20,000.

(ii) For gradual expansion:

In flow through gradual enlargements, the energy losses are significantly reduced due to elimination of the vortices. Experiments on tapered enlargements show that the friction loss factor e_f depends on both the angle of taper, β , and the area ratio A_1/A_2. In turbulent flow, the dependence of e_f on Reynold's Number is small. The value of e_f can be found once the area ratio and angle of taper are known from Figure E3-5. Finding the value of e_f from a diagram by the user of a CAD/CAM program is inconvenient. Therefore, once values of A_1/A_2 and β have been input to the program, a quadratic interpolation is used to approximate all the curves on the diagram and a subroutine in the program calculates e_f in this way.

(iii) For contraction:

The energy loss associated with contraction is different for different entrance geometries. This entrance affect is taken into account by means of an entrance-loss coefficient, see Figure E3-6.

$$e_f = \text{Entrance-loss coefficient} \times e_{f\text{, sharp}} \tag{2-9}$$

From Kay's paper*, $e_{f\text{ sharp}}$ is evaluated in the following way: see Figure E3-7.

$$e_{f\text{, sharp}} = \frac{1 - 2C_c + C_c^2\,(2K_{ds}-1)}{C_c^2} \tag{2-10}$$

where K_{ds} has the same meaning as the sudden expansion case, equation (2-7), and is calculated in the same way. C_c is jet contraction-area ratio, A_2/A_3, see Figure E3-8. As can be seen from Figure E3-3, the flow stream experiences an initial contraction from A_1 to A_2 and then re-expands to

*See previous page.

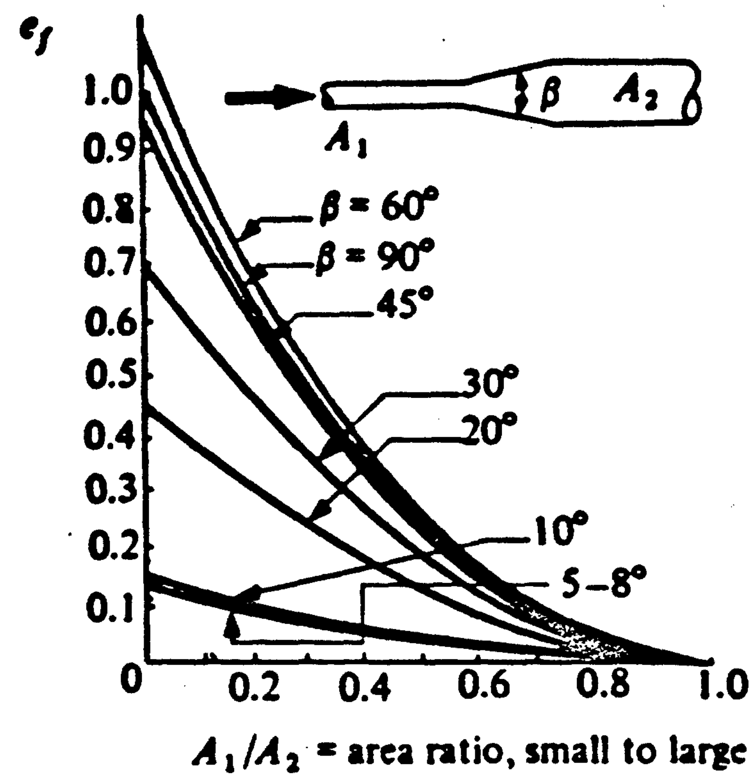

Figure E3-5: Friction-loss factor for turbulent flow through gradual enlargements.

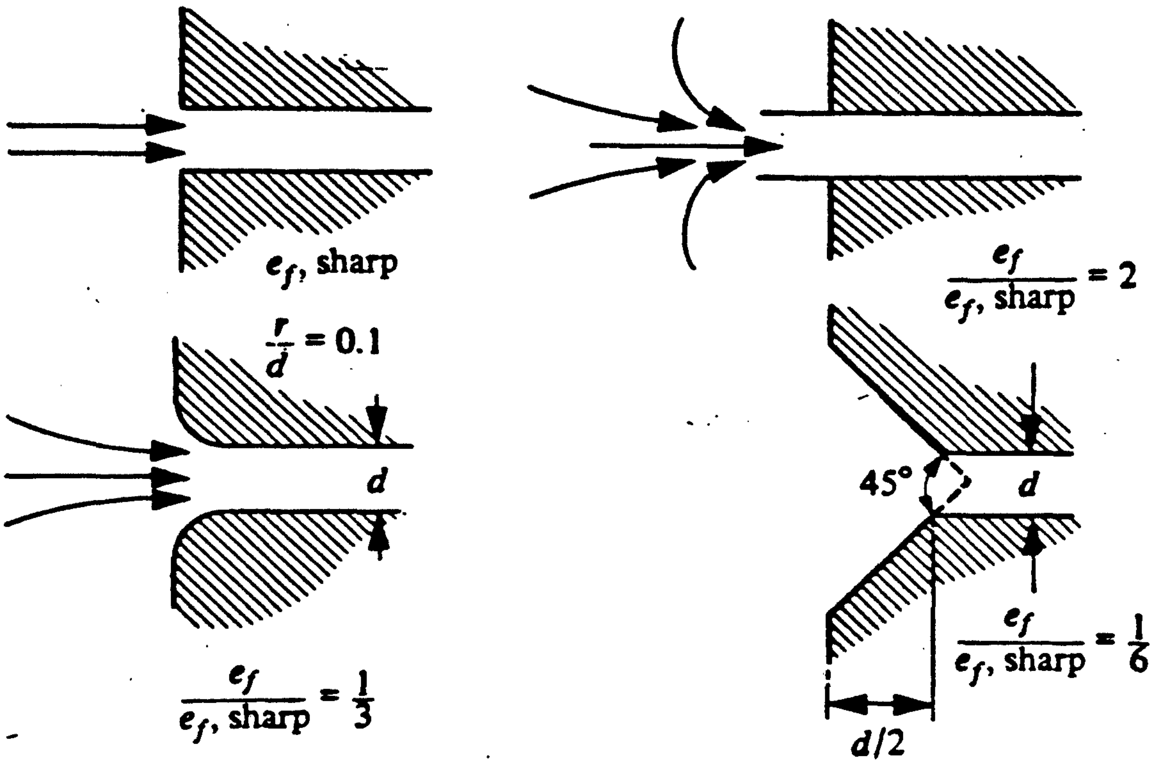

Figure E3-6: Entrance-loss coefficients

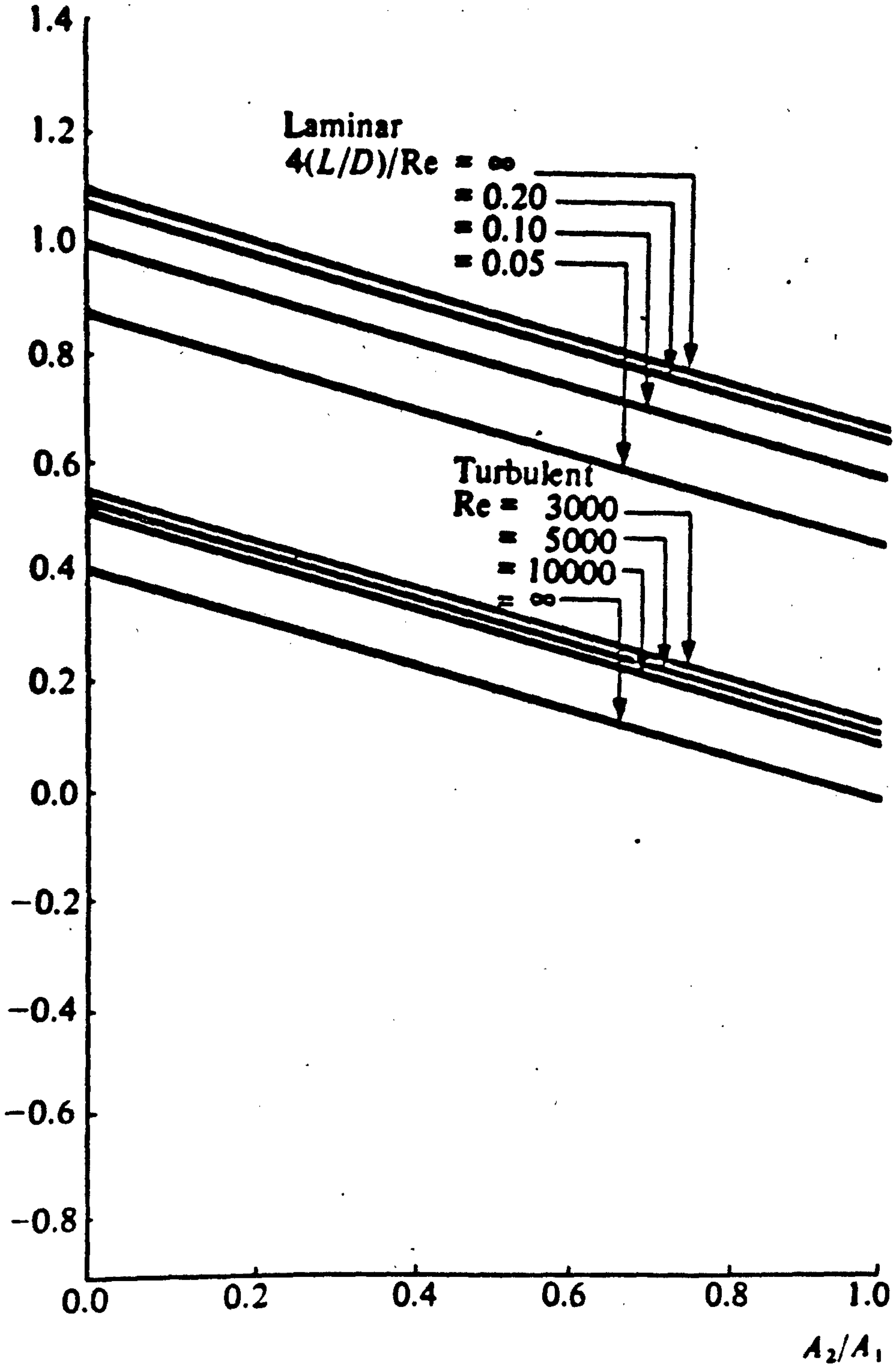

Figure E3-7: Friction-loss factor for sudden contraction

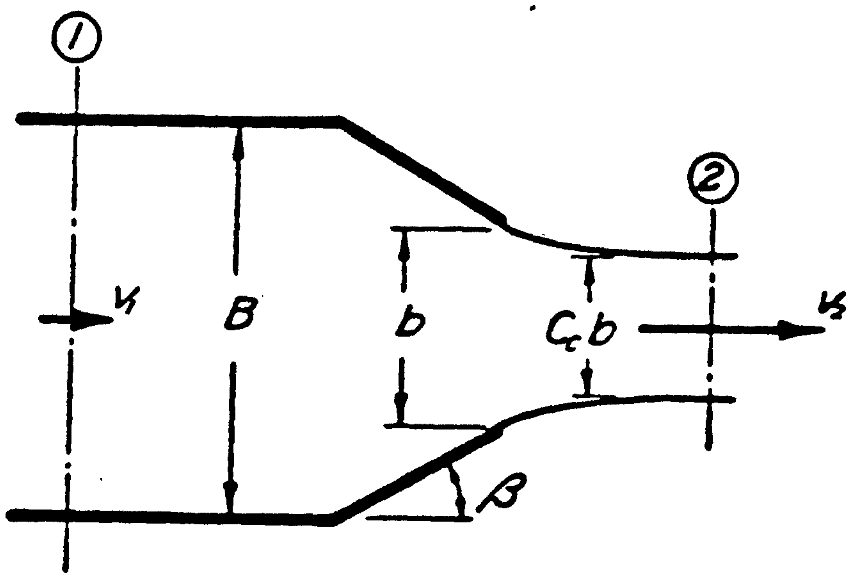

Figure E3-8: Definition sketch for two-dimensional analysis of efflux

A_3, the former is of secondary importance in frictional energy loss. That is why e_f, sharp is a function of C_c rather than A_3/A_1. However, C_c is a function of A_3/A_1, and can be calculated by using linear interpolation based on Table E3-3.*

When the level of molten metal inside the casting cavity is higher than the centerline of the ingate, a back pressure is built up at the vicinity of the ingate; and subsequently, the flow rate decreases. Also, in this situation, the kinetic energy of molten metal inside the cavity is so small that it can be neglected. The potential energy is balanced by the frictional energy loss, which is shown above as a function of the square of velocity. Therefore, the velocity of the molten metal at the ingate becomes a function of $H^{1/2}$ after the level of molten metal becomes higher than the centerline of the ingate, where H is the level difference between the top level in the pouring basin and the top level inside the mold mold cavity.

E3-2-2 Solution of Heat Loss in Gating System

This model is to calculate the heat losses in the gating system so that the pouring temperature can be determined prior to pouring. It is known that if the foundrymen fail to pour a casting at the right temperature, they may have a defective casting due to lack of fill, cold shuts, entrapped sand or gas, hot tears, shrinkage or a poor surface finish. On the other hand, if poured at the correct temperature, the casting can be free of all these defects and in turn make the operation a profitable one.

A heat transfer simulation for the case of a sand runner by means of electrical analog was conducted at Franklin Institute, Philadelphia, PA. This technique avoids the trial and error procedure commonly used to adjust pouring temperature enabling the same quality casting to be obtained on the first pour. The temperature loss within the gating system can be represented by the following equations:

$$\Delta T = \frac{Pt_o\ (T_p - T_o)\ \exp\ (Z^2)\ \mathrm{erfc}\ (Z)}{A^{**}\ (d_L)\ (C_L)} \qquad (2\text{-}11)$$

ΔT = Temperature loss of liquid metal, deg F.

p = Wetted perimeter, ft.

t_o = Transient time of an element of metal, hr.

$$Z = h\ (A/kdC)^{1/2}$$

*H. Rouse, Elementary Mechanics of Fluids, John Wiley (New York, 1946).

Table E3-3. Coefficient of jet-contraction for the two-dimensional boundary characteristics of Figure 2-8*

$\frac{b}{\beta}$	$\beta = 45$ C_c	$\beta = 90$ C_c	$\beta = 135$ C_c	$\beta = 180$ C_c
0.0	0.746	0.611	0.537	0.500
0.1	0.747	0.612	0.547	0.513
0.2	0.747	0.616	0.555	0.528
0.3	0.748	0.622	0.566	0.544
0.4	0.749	0.631	0.580	0.564
0.5	0.752	0.644	0.599	0.586
0.6	0.758	0.662	0.620	0.613
0.7	0.768	0.687	0.652	0.646
0.8	0.789	0.722	0.698	0.691
0.9	0.829	0.781	0.761	0.760
1.0	1.000	1.000	1.000	1.000

*H. Rerise, Elementary Mechanics of Fluids, John Wiley (New York, 1946)

T_p = Original temperature of liquid alloy, deg F

A** = Cross-sectional area of runner, square ft

d_L = Density of liquid metal, lb/(cubic ft)

C_L = Specific heat of liquid metal, BTU/lb/deg F

k = Thermal conductivity of mold, BTU/hr/ft/deg F

d = Density of mold, lb/(cubic ft)

T_o = Original temperature of mold, deg F

C = Specific heat of mold, BTU/lb/deg F

t = Pouring time, hr

From the equation above, it is seen that a finite heat transfer coefficient h at the mold wall partially controls the heat loss in the gating system. There is a correlation of the heat transfer coefficient at the interface with interface temperature. A discussion of interface temperature must recognize that there are two interface temperatures, not one, in a situation where a heat transfer coefficient is used. The two temperatures are the alloy surface temperature and the mold surface temperature. The coefficient was found to be strongly related to the alloy surface temperature, but independent of mold surface temperature. The heat transfer coefficient is found to dynamically decrease from a maximum value to a steady value if the casting contracts away from the mold. In the case of this system, the maximum value is used because the steady state is not reached. The data relating the interface temperature to the heat transfer coefficient can be found in Sully's paper*. A value of 148 BTU/(hr. square ft.deg.F) of the heat transfer coefficient for steel/sand was used in this analysis.

One thing must be noted that "start of pour" for equation (2-11) was defined as the start of steady flow through the exit, and this instant coincides with the end of the initial filling transient. The flow velocity in the initial filling transient is higher than it is during the steady flow. Therefore, the duration of time that an element of fluid is in contact with the runner wall for the initial transient is shorter than the steady flow and results in smaller temperature loss for this initial transient than the steady flow. By

*L.T.D. Sully, "The Thermal Interface Between Casting and Chill Molds, AFS Transactions, 84, 1976, pp. 735-744

the time the steady flow begins, the runner wall has been partially heated by the metal that passes through during the filling transient. Consequently, the high velocity during the initial filling transient has the beneficial effect of reducing the severity of the early peak temperature loss.

E3-3 EXECUTION

The computer program for these calculations, (a) filling rate and velocity and (b) heat loss in a casting gating system, is named FITLGS. The program was used to simulate the gating system (Figure E3-1) used for the stepped plate casting experiments (note the main report). Figure E3-9 illustrates the use of the program. Figure E3-10 shows the results of the heat loss computation. The program, FITLGS, is interactive and can be run from a terminal or screen by responding to queries from the program. The user should prepare for use of the program by making a dimensioned sketch of the gating system. To start the program an EXecute FITLGS. FOR command is given. Then queries are answered by the user after the " ".

```
 .EX FITLGS.FOR
FORTRAN 5A(621): FITLGS.FOR
MAIN.   OCTAL PROG SIZE=330    + COMMON=132
POLE    OCTAL PROG SIZE=225    + COMMON=2
PLDR    OCTAL PROG SIZE=302    + COMMON=3
TLDR    OCTAL PROG SIZE=342    + COMMON=3
UPDA    OCTAL PROG SIZE=1244   + COMMON=106
FACT    OCTAL PROG SIZE=40     + COMMON=7
FELC    OCTAL PROG SIZE=243    + COMMON=42
FESE    OCTAL PROG SIZE=56     + COMMON=27
FEGE    OCTAL PROG SIZE=1525   + COMMON=1
INFO    OCTAL PROG SIZE=462    + COMMON=13
TLIGS   OCTAL PROG SIZE=2130   + COMMON=11
LINK:   Loading
```

Figure E3-9: Example execution of program FITLGS
(Sheet 1 of 6).

```
[LNKXCT FITLGS execution]

IF YOU WANT TO CALCULATE THE FILLING TIME
ONLY, ENTER 1
IF YOU WANT TO COMPUTE TEMPERATURE LOSS IN THE GATING
SYSTEM ALSO, ENTER 2

>2

WHAT IS THE NUMBER OF PARTS OF THE GATING SYSTEM
WHICH CONTRIBUTE TO THE POTENTIAL ENERGY DIFFERENCE?
ENTER THE DATA BY A FREE I FORMAT

>3

ENTER THE DIMENSIONS OF THOSE PARTS IN INCHES
ONE TO A LINE, USING FREE F FORMAT

>8.0
>8.0
>0.6875

POTENTIAL ENERGY=   0.447E+02

ENTER THE DIAMETER OF THE RUNNER IN INCHES

>1.375

ENTER THE NUMBER OF CHANNEL SEGMENTS TO THE GATING
SYSTEM, INCLUDE HORIZONTAL AND VERTICAL SEGMENTS

>2

ENTER THSE LENGTH OF THE CHANNEL SEGMENTS
ONE TO A LINE, IN INCHES

>8.0
>2.0

THE TOTAL LENGTH OF CHANNEL=   10.0000 INCHES

THE RATIO BETWEEN THE LENGTH AND DIAMETER OF THE RUNNER
PARTS
                0.727E+01

ENTER THE NUMBER OF FITTINGS (CHANGES IN
DIRECTION) FOR THE GATING SYSTEM, SEE TABLE 2-2
```

Figure E3-9: Example execution of program FITLGS
(Sheet 2 of 6)

```
ENTER INFORMATION ABOUT THE FITTINGS USING A NUMBER CODE,
ONE NUMBER TO A LINE
IF IT IS A 90 DEGREE ELBOW, STANDARD RADIUS ENTER 1
IF IT IS A 90 DEGREE ELBOW, MEDIUM RADIUS, ENTER 2
IF IT IS A 90 DEGREE ELBOW, LONG SWEEP, ENTER 3
IF IT IS A 90 DEGREE ELBOW, SQUARE, ENTER 4

>4

THE EQUIVALENT RLA/DR FOR THE FITTINGS
                0.650E+02

TOTAL EQUIVALENT RLA/DR= 0.723E+02

ENTER THE ABSOLUTE ROUGHNESS OF THE MOLD MATERIALS
IN INCHES, TO USE THE DEFAULT VALUE OF 0.012, ENTER 1
TO USE ANOTHER VALUE, ENTER 2

>1

ENTER THE NUMBER OF THE CONTRACTIONS IN THE CROSS
SECTION OF THE FLOW CHANNEL WITHIN THE GATING SYSTEM

>2

ENTER INFORMATION ABOUT THE CHARACTERISTICS OF
THE CONTRACTION (SEE FIGURE 2-6) USING A NUMBER CODE
SHARP CONTRACTION, ENTER 1
TURBULENT SHARP CONTRACTION, ENTER 2
RADIUS OF THE CORNER/DIAMETER OF RUNNER=0.1, ENTER 3
CONTRACTION ANGLE=45, ENTER 4
AND ALSO ENTER THE DIAMETER OF THE LARGE SECTION AND
SMALL SECTION ON THE SAME LINE IN INCHES

>4 200.0 1.375
>1 2.0 1.375

ENTER THE NUMBER OF SUDDEN EXPANSIONS IN THE GATING
SYSTEM

>1

ENTER THE DIAMETER OF THE LARGE SECTION AND THE SMALL
SECTION IN INCHES

>2.0 1.0

ENTER THE NUMBER OF GRADUAL EXPANSION PARTS
OF THE GATING SYSTEM
```

Figure E3-9: Example execution of program FITLGS
(Sheet 3 of 6)

```
>0

ENTER THE VALUE OF THE DENSITY (POUNDS PER CUBIC FOOT)
AND VISCOSITY (FOOT SQUARE PER SECOND) OF THE FLUID
TO USE THE DEFAULT VALUES OF 449.0 AND 0.00134 FOR STEEL,
ENTER 1
TO USE OTHER VALUES, ENTER 2

>1

ENTER THE VOLUME OF THE CAVITY WHICH IS BELOW THE
CENTER LINE OF THE INGATE IN CUBIC INCHES

>290.0

ENTER THE HORIZONTAL CROSS SECTIONAL AREA OF THE
CAVITY IN SQUARE INCH

>201.6

ENTER THE NUMBER OF THE PARTS OF THE CAVITY, WHICH
ARE ABOVE THE CENTER LINE OF THE INGATE

>1

ENTER THE HIGHTS OF THOSE PARTS ONE TO A LINE
IN INCHES

>0.6875

ENTER THE DIAMETERS AND HEIGHTS OF THE RISERS
IN INCHES

>5.0 4.5

THE RELATIVE ROUGHNESS= 0.873E-02

THE FRICTION FACTOR= 0.394E-01

THE FRICTION ENERGY LOSS COEFFICIENT DUE TO UNIFORM
SEGMENTS OF THE GATING SYSTEM
                0.142E+01

CONTRACTION ENERGY LOSS COEFFICIENT= 0.172E+00

SUDDEN EXPANSION ENERGY LOSS COEFFICIENT= 0.274E+00

THE VELOCITY OF THE FLUID AT THE INGATE WHEN THE
FLUID LEVEL IN THE CAVITY IS BELOW THE CENTER LINE OF
```

Figure E3-9: Example execution of program FITLGS
(Sheet 4 of 6)

```
THE INGATE IN FEET PER SECOND 0.435E+01

THE TIME REQUIRED TO FILL THE CAVITY BELOW THE
CENTER LINE OF THE INGATE IN SECONDS =  3.75

THE TIME REQUIRED TO FILL THE PART OF THE CAVITY WHICH
IS ABOVE THE CENTER LINE OF THE INGATE, IN SECONDS=  1.99

THE TIME REQUIRED TO FILL THE RISER IN SECONDS=  1.39

THE TOTAL TIME REQUIRED, IN SECOND =  7.12

THE NUMBER OF ITERATIONS=  5

ENTER THE INITIAL TEMPERATURE OF MOLTEN METAL
IN DEGREE F

>3000.0

ENTER THE INITIAL TEMPERATURE OF MOLD MATERIAL
IN DEGREE F

>100.0

ENTER THE HEAT TRANSFER COEFFICIENT
IN BTU/(HR*FT**2*F)
TO USE THE DEFAULT VALUE OF 147.732 FOR STEEL, ENTER 1
TO USE ANOTHER VALUE, ENTER 2

>1

ENTER THE HEAT CAPACITY OF MOLTEN METAL
IN BTU/(LB*F)
TO USE THE DEFAULT VALUE OF 0.16 FOR STEEL, ENTER 1
TO USE ANOTHER VALUE, ENTER 2

>1

ENTER THE THERMAL CONDUCTIVITY OF MOLD MATERIAL
IN BTU/(FT*F*HR)
TO USE THE DEFAULT VALUE OF 0.9 FOR SAND, ENTER 1
TO USE ANOTHER VALUE, ENTER 2

>1

ENTER THE DENSITY OF MOLD MATERIAL
IN LB/(FT**3)
TO USE THE DEFAULT VALUE OF 99.0 FOR SAND, ENTER 1
TO USE ANOTHER VALUE, ENTER 2
```

Figure E3-9: Example execution of program FITLGS
(Sheet 5 of 6)

```
>1

ENTER THE HEAT CAPACITY OF MOLD MATERIAL
IN BTU/(LB*F)
TO USE THE DEFAULT VALUE OF 0.29 FOR SAND, ENTER 1
TO USE OTHER VALUE, ENTER 2

>1

ENTER THE NUMBER OF TIMES AFTER THE
INITIATION OF THE POUR WHEN YOU DESIRE A
CALCULATION OF TEMPERATURE LOSS
USING FREE I FORMAT

>10

ENTER THE TIMES OF INTEREST ONE TO A LINE IN SEC

>1.0
>1.5
>2.0
>2.5
>3.0
>4.0
>5.0
>5.5
>6.0
>7.0

TIME INSTANCE INTERESTED  TEMPERATURE LOSS  TEMPERATURE
    (SECONDS)                (DEGREES F)      (DEGREES F)
         1.0                     6.9            2993.1
         1.5                     6.3            2993.7
         2.0                     5.9            2994.1
         2.5                     5.6            2994.4
         3.0                     5.3            2994.7
         4.0                     4.8            2995.2
         5.0                     4.5            2995.5
         5.5                     4.4            2995.6
         6.0                     4.2            2995.8
         7.0                     4.0            2996.0
```

Figure E3-9: Example of execution of program FITLGS
(Sheet 6 of 6)

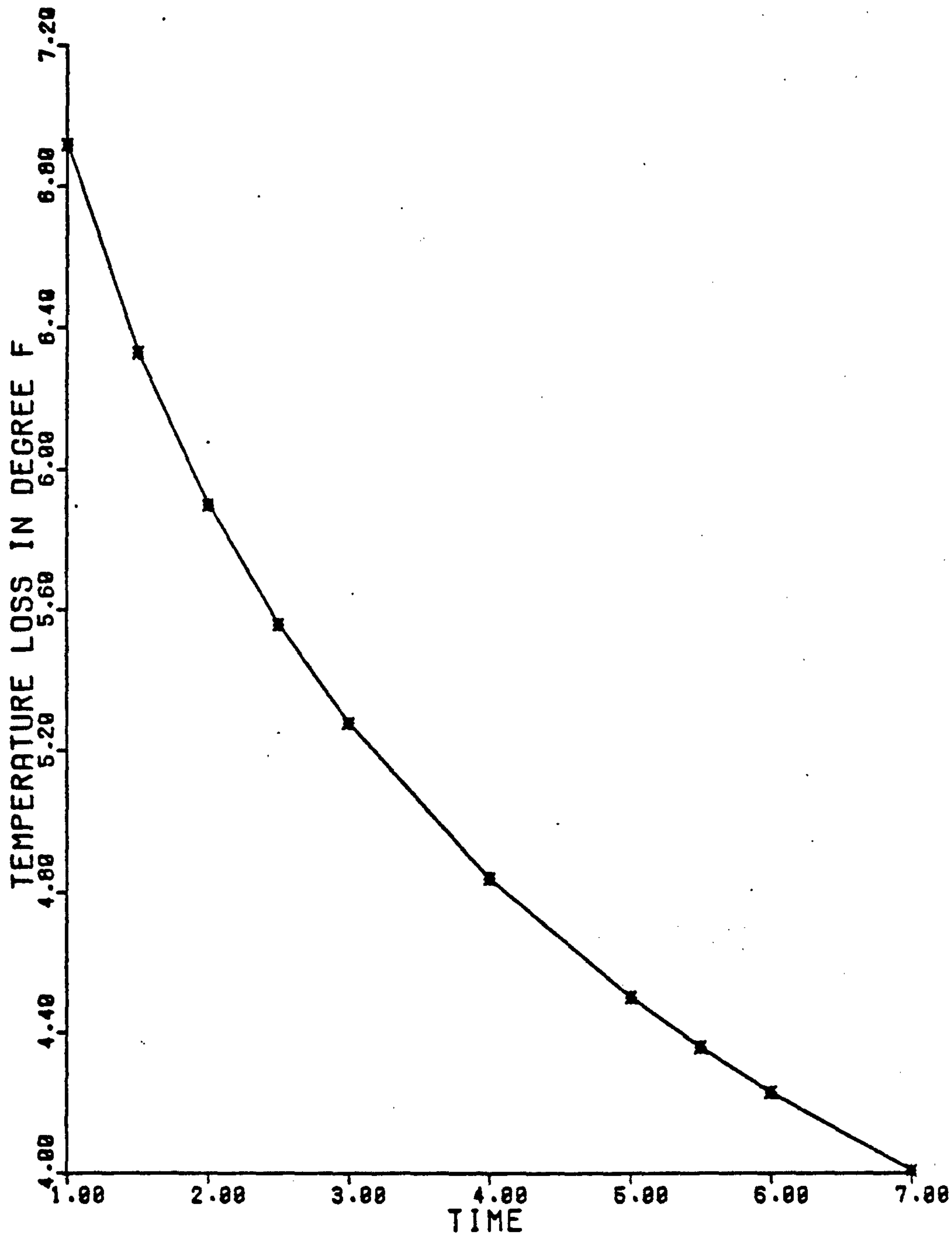

Figure E3-10: Temperature loss vs. time in gating system.

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